Designing for Multispecies Cohabitation: The Case of Prosthetic Habitat-Structures

Daniel Parker

ORCID identifier: 0000-0001-5325-4176

Doctor of Philosophy (PhD)

May 2024

Faculty of Architecture, Building and Planning, The University of Melbourne

Thesis submitted in total fulfilment of the PhD degree

Abstract

This thesis develops novel approaches to improve design for multispecies cohabitation. As anthropogenic activities continue to harm individuals, diminish biodiversity, and lead to species extinctions, there is an increasing need for designs that better facilitate the coexistence of humans and other living beings. Such designs pose complex practical and theoretical challenges that span multiple scales, stakeholders, and fields of knowledge. Drawing from architectural design, biological sciences, and environmental humanities, this thesis introduces the idea of 'prosthetic habitat-structures' as a promising approach for supporting mutually beneficial cohabitation.

Prosthetic habitat-structures are interventions that add habitat opportunities by aiding, extending, or grafting onto existing structures. This thesis focuses primarily on the design of prosthetic tree hollows. These structures are an important conservation measure in response to the global decline in large old trees. The hollows that develop in these trees provide crucial habitat for many species of birds, mammals, and reptiles. However, tree hollows can take several decades to form and are in short supply in urban and agricultural areas. Existing human-made replacements, such as nest boxes, have known limitations.

In response to the challenges of designing for multispecies cohabitation, this thesis adopts and extends state-of-the-art research and practice that recognise more-than-human capacities for culture, creativity, and collaboration. It proposes that: (a) better knowledge of existing and potential cultures shared between human and nonhuman urban dwellers can help imagine paths toward multispecies cohabitation; (b) computer-assisted techniques can support the development of novel approaches to implementing and evaluating habitat structures; and (c) prototyping of prosthetic habitat-structures for and with human and nonhuman stakeholders can cultivate persuasive proposals for multispecies cohabitation.

To test these hypotheses, the chapters in this thesis use case studies and design experiments in Australia and Italy, focusing on humans, owls, and other arboreal life. The resulting field installations, theoretical frameworks, recommendations, workflows, models, and practical toolkits aim to benefit communities that include both human and nonhuman beings. These outcomes contribute to interdisciplinary efforts to address ongoing habitat destruction that diminishes biological and cultural diversity. This thesis demonstrates how design that integrates cultural, ecological, and technical evidence can advance the goals of cohabitation, expanding possible futures beyond the mere mitigation of anthropogenic harm.

Graphic abstract

Prosthetic habitat-structures for multispecies cohabitation illustrated through a prosthetic tree hollow (middle circle) developed with and for birds, mammals, fungi, and plants (outer circles). From top clockwise: humans forage fungal spores and debris as materials for the prosthetic hollow; mycelium grows through the debris into the shape of the hollow; birds such as owls use the hollow; bryophytes colonise the hollow over time; insects or ground-dwelling mammals have opportunities to use the hollow after it reaches the end of its useful life in a tree; trees regenerate and the materials of the biodegradable hollow return to the soil.

Declaration

This thesis:

i. comprises only of my original work towards the Doctor of Philosophy except where indicated in the preface;

ii. gives due acknowledgement in the text to all other material used; and

iii. is fewer than the maximum word limit in length, exclusive of tables, maps, bibliographies, and appendices.

Preface

This thesis addresses challenges that require interdisciplinarity and collaboration. Building on my background in digital architectural design, the work presented in this thesis is the result of valuable collaborations with designers, ecologists, animals, and others.

As expected in a 'Thesis with Publication', the chapters appear as co-authored articles for academic journals. By the submission date, I have published three articles, submitted two others, and presented one at an international conference (Table 1). I acknowledge the contributions of collaborators and detail their involvement in the 'author contributions' and 'acknowledgements' sections of each chapter. The publications in this thesis reach audiences in art, design, ecology, humanities, and interdisciplinary journals, highlighting the relevance and significance of the work across various fields. The Australian Government Research Training Program Scholarship and the Faculty of Architecture, Building and Planning at the University of Melbourne provided partial support for this research. I acknowledge all other funding sources in the respective sections of each publication.

Table 1. An overview of the publications in this thesis.

Chapter	Status	Audience	Peer-review	Work prior to PhD
1	Published by Leonardo on August 01 2022	Art and design	Two reviewers	Prototyping and the first part of writing
2	Published by Transpositions on April 12 2022	Environmental humanities	Two reviewers (blinded)	None
3	Submitted for publication to People and Nature on April 23 2024	Interdisciplinary	Two reviewers	None
4	Published by Methods in Ecology and Evolution on February 13 2022	Biological sciences	Four reviewers	Prototyping and installation of prototypes
5	Submitted for publication to Conservation Science and Practice on May 25 2024	Biological sciences	Two reviewers (blinded)	None
6	Presented at the International Conference on Construction, Energy, Environment and Sustainability on June 27 2023	Built environment	Extended abstract of conference paper reviewed by organising committee	None

Chapter 1

Parker, Dan, Stanislav Roudavski, Bronwyn Isaac, and Nick Bradsworth. 2022. "Toward Interspecies Art and Design: Prosthetic Habitat-Structures in Human-Owl Cultures." *Leonardo* 55 (4): 351–56. https://doi.org/10/hwkm.

Chapter 2

Parker, Dan, Kylie Soanes, and Stanislav Roudavski. 2022. "Interspecies Cultures and Future Design." *Transpositiones* 1 (1): 183–236. https://doi.org/10/gpvsfs.

Chapter 3

Parker, Dan, Kylie Soanes, and Stanislav Roudavski. 2024. "Wings Over Concrete: Exploring Human-Owl Cohabitation in Urban Landscapes."

Chapter 4

Parker, Dan, Stanislav Roudavski, Therésa M. Jones, Nick Bradsworth, Bronwyn Isaac, Martin T. Lockett, and Kylie Soanes. 2022. "A Framework for Computer-Aided Design and Manufacturing of Habitat Structures for Cavity-Dependent Animals." *Methods in Ecology and Evolution* 13 (4): 826–41. https://doi.org/10/gpggfj.

Chapter 5

Parker, Dan, Stanislav Roudavski, Chiara Bettega, Luigi Marchesi, Paolo Pedrini, Mattia Brambilla, and Kylie Soanes. 2024. "Which Design Is Better? A Lifecycle Approach to the Sustainable Supply and Replacement of Artificial Habitat-Structures."

Chapter 6

Parker, Dan, Kylie Soanes, Chiara Bettega, Luigi Marchesi, Paolo Pedrini, Chiara Fedrigotti, Mattia Brambilla, and Stanislav Roudavski. 2023. "An Online Tool to Design Custom Habitat-Structures with and for Tree-Dwelling Species." In *Proceedings of the International Conference on Construction, Energy, Environment and Sustainability*, edited by Julieta António, Nuno Simões, and Michael Lacasse, 1–9. Funchal: Itecons.

Acknowledgements

I am hugely grateful for all the support I have received during my PhD candidature.

To my advisory committee, especially Dr Stanislav Roudavski and Dr Kylie Soanes, thank you for shaping this thesis into something that we can all be proud of. I appreciate your insightful guidance and all the time and energy you have put into our research. It is a privilege to work on such fascinating and meaningful topics, and I am excited to continue the projects we have started.

Thank you to family and friends for the unwavering support, good company, and genuine interest in my work. To my family, I cannot say enough how much I appreciate your care for each other and the places we love—the gardens; the homes; the forests. Thank you everyone for the positivity (and sub-par owl banter) that has kept me afloat through challenging times.

I have been fortunate to meet many brilliant people during my research journeys in Australia, Italy, England, Denmark, and Aotearoa/New Zealand. I would like to thank all collaborators, participants, lab members, co-authors, reviewers, and examiners for your generous contributions to the research in this thesis.

Table of contents

Introduction

How can design support multispecies cohabitation, where human and nonhuman organisms coexist and thrive? The need to address this question has become increasingly urgent in the context of unfolding planetary crises affecting human and nonhuman lives. This thesis responds by introducing novel design approaches to support multispecies cohabitation, setting out to benefit communities of multiple forms of life whose livelihoods depend on the actions of humans. To do this, I conceptualise and test prosthetic habitat-structures as a means to facilitate mutually beneficial coexistence among humans, other mammals, birds, fungi, plants, and other organisms. Prosthetic habitat-structures are interventions that add habitat opportunities, such as nesting sites, by aiding, extending, or grafting on existing structures. The research presented in this thesis contributes to efforts across several disciplines grappling with the challenge of transforming degraded ecosystems into places where multispecies communities are abundant, diverse, and flourishing. I argue that the best way to develop prosthetic habitat-structures is through the involvement of nonhuman beings who use or build them. To unpack this argument, I structure this Introduction into sections that outline the:

i. calls for multispecies cohabitation from fields within the environmental humanities, biological sciences, and built environment;
ii. idea that prosthetic habitat-structures can be produced for, with, or by nonhuman stakeholders; and
iii. state-of-the-art methods that this thesis extends to develop new knowledge on cohabitation and improve prosthetic habitat-structures.

I conclude by explaining the thesis narrative that emerges from the chapters.

1 Designing for multispecies cohabitation

1.1 What is multispecies cohabitation?

Multispecies cohabitation offers an important, hopeful, and yet feasible aspiration for design that supports sustainable and fair co-existence of multiple species (Roudavski 2020). The notion of multispecies cohabitation draws from influential work in the environmental humanities, which explores how humans can live alongside other living beings in ways that minimise harm and risk, while supporting mutual flourishing (Hubbell and Ryan 2022). This work spreads into disciplines including anthropology, geography, anthrozoology, multispecies studies, ecological justice, Indigenous scholarship, and more-than-human ethnographies. Multispecies cohabitation connects to the more ambitious approaches to conservation, which aspire to cultivate convivial relationships among humans, ecosystems, and nonhuman inhabitants regardless of their utility to perceived human interests (Büscher and Fletcher 2019; Taylor et al. 2020; Kopnina 2012). The goal of cohabitation is to satisfy both human and nonhuman interests (Frank, Glikman, and Marchini 2019; Carter and Linnell 2023), leading to the conservation of biodiversity and reduction of extinction risks (Lawson and Nguyen-Van 2020). The coexistence of multiple species is unavoidable and can lead to both co-benefits and conflicts (Knight 2001; Frank and Glikman 2019). More convivial cohabitation depends on actions across multiple disciplines, knowledge bases, scales, and stakeholders. For instance, cohabitation can be achieved through such measures as geographical zoning, regulation and policy such as building codes, or interventions that aim to reduce interspecies conflict and encourage mutual learning to live in proximity (Boonman-Berson 2018). My research explores how design can help to achieve multispecies cohabitation.

1.2 Why is design for cohabitation needed?

There is an acute need to develop strategies for cohabitation in response to human activities that diminish biological and cultural diversity. Since 1970, global populations of mammals, birds, fish, reptiles, and amphibians have decreased by an average of 69% (World Wildlife Fund 2022). Extinctions are also accelerating at alarming rates (Bellard et al. 2012; Ceballos et al. 2015; Ceballos, Ehrlich, and Raven 2020). Globally, one third of tree species are now threatened with extinction, which has grave implications for the livelihoods of humans as well as the survival of many animals, plants, and fungi (Rivers et al. 2023). Human-induced habitat loss displaces or harms countless organisms. For example, in Australia, forest and woodland clearing between 2000 and 2017 destroyed 7.7 million hectares of habitat suitable for threatened species (Ward et al. 2019). Many organisms cannot adapt to the rapid rate of human-induced environmental change (McDonnell and Hahs 2015). Habitat and biodiversity losses can also destroy or alter cultures, including worldviews, languages, knowledge, and practices that relate to the land and its nonhuman inhabitants (Maffi 2018). Reversing these trends depends on cultures which inform the will for humans to coexist with other forms of life (Rupprecht 2017). Consideration of nonhuman cultures is also critical. Human and nonhuman cultures alike emerge through socially transmitted information (Mesoudi 2016). Biologists have shown that human activities disrupt culturally informed foraging strategies, migration patterns, and communication in many living communities (Brakes et al. 2021). An example is the decreasing tool-use by monkeys in areas where human activities are particularly pervasive (Roncero, de Mendonça-Furtado, and Izar 2023). The damage to biodiversity, habitats, and cultures has devastating implications for the quality of human and nonhuman lives, calling for approaches that are innovative, interdisciplinary, and inclusive (Díaz et al. 2018; Sterling et al. 2017; Díaz et al. 2019).

1.3 How does design support or hinder cohabitation?

Design of the built environment has a significant role in supporting cohabitation. The built environment comprises areas that humans have modified to inhabit, including buildings, parks, and infrastructure such as roads. Despite being significantly human modified, built environments function as ecosystems that sustain new combinations and abundances of species (Parris 2016). Such novel ecosystems can support, and are crucial for, many species (Australian Conservation Foundation 2020; Ives et al. 2016; Soanes and Lentini 2019; McDonnell and Hahs 2013; Lowry, Lill, and Wong 2013). Humans can create habitats accidentally or deliberately (Grose 2014). For instance, buildings and bridges designed for humans have both intentionally and unintentionally provided roosting sites for bats (Mering and Chambers 2014). Even in cases where the conservation of threatened species occurs elsewhere, cities are important for encouraging positive relationships between humans and other living beings (Dunn et al. 2006). This is because humans are more likely to engage in conservation action or other pro-environmental behaviours when they have direct experiences with biodiversity in their daily lives, which primarily takes place in cities as urbanisation increases (*ibid.*). In reverse, disconnection from biodiversity can intensify disgust towards other living beings (Soga et al. 2023) or make it difficult to rally the resources and ambitions needed to address ecological issues (Soga and Gaston 2016; Miller 2005). For these reasons, urban ecologists work to overcome misconceptions that cities lack conservation value (Soanes, Sievers, et al. 2018).

Researchers and practitioners in the built environment increasingly recognise their responsibility to address pervasive anthropogenic damage (Oke et al. 2021). For example, the Built Environment Declares movement saw thousands of practices in architecture, landscape architecture, urban planning, construction, and engineering express their commitment to address climate and biodiversity emergencies. These commitments are necessary as the status quo of development in the built environment typically homogenises habitats and reduces the quality and availability of habitable areas (McKinney 2006; 2008). Researchers stress that more is needed to overcome long-standing anthropocentric attitudes that do not adequately account for nonhuman needs, judge projects according to human-centred criteria for success, and result in urban developments that exclude or exploit nonhuman inhabitants (Wolch and Owens 2017; Rawes 2013; Wolch, West, and Gaines 1995; Loh et al. 2020).

Current best practices shift away from prevailing approaches to design that disregard nonhuman lives towards alternatives that strive to cultivate thriving ecosystems. There is burgeoning body of practices and theories that consider more-than-human concerns in the design and planning of built environments (Parris et al. 2018). Often citing scholarship from environmental humanities and ecological sciences as well as Indigenous knowledge, such non-anthropocentric design recognises the complex relations and interdependencies of human and nonhuman entities including land, animals, and plants (Maller 2021). Labels for approaches that share similar goals include nature-positive (Birkeland 2022), biodiversity-sensitive (Garrard et al. 2018), animal-aided (Weisser and Hauck 2017), wildlife-inclusive (Apfelbeck et al. 2020), multispecies (Metcalfe 2023), ecocentric (St. Pierre 2015), and ecological design (Delancey 2004). These approaches call for collaboration across many disciplines, including researchers, urban planners, architects, landscape designers, engineers, urban ecologists, governments, environmental practitioners, conservationists, and land managers (Felson 2013; Kay et al. 2022). Going further, emerging approaches seek to involve nonhuman organisms as clients, stakeholders, and participants in design processes for urban development (Hernandez-Santin et al. 2023), governance (Sheikh, Mitchell, and Foth 2023), and interaction design (Borthwick, Tomitsch, and Gaughwin 2022). However, the goals, techniques for design, and criteria for success remain insufficiently defined, requiring further theorisation and practical experimentation. Frameworks on the topic of multispecies cohabitation highlight that much further work is necessary to develop ways of nurturing relationships among human and nonhuman inhabitants of cities, designing for functional ecologies, and integrating nonhuman stakeholders as participants in design processes (Hernandez-Santin et al. 2022). To engage with these challenges of designing for multispecies cohabitation, this thesis introduces the concept of prosthetic habitat-structures.

2 The case of prosthetic habitat-structures

2.1 What are prosthetic habitat-structures?

Building on my background in architecture, I investigate how the design of physical structures can support multispecies cohabitation. Architectural designers, whose work uses physical structures to support dwelling, are familiar with the provision of habitat structures (Roudavski 2018). Ecologists describe habitat structures as the physical arrangement of objects in space that organisms inhabit, such as features of trees, shrubs, and woody debris (Bell, McCoy, and Mushinsky 1991). Conservationists make 'artificial habitat-structures' to maintain or improve the state of individuals or populations, including their survival, growth, reproduction, and abundance (Watchorn et al. 2022). Managers generally deploy artificial habitat-structures to support at least one of four behaviours: nesting, resting, feeding, or moving (see use of artificial refuges in Cowan et al. 2021). Examples include attaching nest boxes to buildings for birds (Dulisz et al. 2021), embedding artificial dens within rock piles to provide shelter for marsupials (Cowan et al. 2023), retrofitting seawalls with rockpools that support marine life (Hall et al. 2019), and installing rope bridges to provide safe crossings for mammals (Soanes, Taylor, et al. 2018).

Extending the term 'artificial habitat-structures', I conceptualise prosthetic habitat-structures as interventions that add habitat opportunities by aiding, extending, or grafting on existing structures. These interventions exist on a spectrum between anthropogenic and biotic, in recognition that all habitat-structures develop through interspecies interactions that can be more or less human-made. As such, 'prosthetic' habitat-structures include what would usually be called 'artificial' and 'natural' habitat-structures but move beyond dualist worldviews that position humans as separate to nature and lead to resource exploitation or other ecological problems (Escobar 2018). Prosthetic habitat-structures can include designs for, with, and by nonhuman stakeholders such as trees and birds (Holland and Roudavski 2024), acknowledging that prosthesis occurs in nonhuman animals who make tools and transform environments they inhabit (Grosz 2005). For instance, wasps and swallows build prosthetic habitat-structures that transform the flat surfaces of human buildings into places where they can nest. 'Artificial' and 'natural' habitat-structures are still useful terms when communicating to audiences in the biological sciences, and I use them throughout this thesis. However, they are less accurate as methods develop for including nonhuman collaborators in design. To illustrate using a project that I worked on, the addition of soft, biodegradable, and living materials onto a building facade can enable micro-organisms or insects to decompose the structure as well as bees to excavate their nests in the way that they prefer (Parker et al. 2023). As with medical contexts, such as blades that make humans run faster or 3D-printed limbs for animals with amputations, these prosthetic additions can restore, enhance, or open new functions without necessarily appearing the same as biological analogues. Therefore, designers can strive to create prosthetic-habitat structures that go beyond minimum requirements for survival, offering a fitting approach to support biodiversity in novel ecosystems where the restoration of exact past conditions can be practically impossible or undesirable for existing inhabitants.

2.2 Why are prosthetic habitat-structures needed?

The idea of humans installing habitat structures that differ from biotic analogues might initially seem like a perverse interference. However, prosthetic habitat-structures help address the scarcity of habitat structures in novel ecosystems that are already significantly human-altered, serving as measures to support the livelihoods of many organisms. The decline in numbers of large old trees is a significant example that characterises the challenges in other cases and serves as a central focus of this thesis. In particular, I consider the hollows in trunks and branches where organisms nest and shelter, which can take centuries to develop (Le Roux, Ikin, Lindenmayer, Manning, et al. 2014). It is critical to minimise further destruction and revegetate ecosystems through such strategies as controlling urban sprawl, expanding green space, and protecting large old trees (Ikin et al. 2015). However, existing management strategies, policy, and conservation measures are insufficient to mitigate the reduction in availability of habitat structures in urban and agricultural areas (Le Roux, Ikin, Lindenmayer, Blanchard, et al. 2014). Human provision of habitat structures can assist in areas where revegetation is not feasible, such as on buildings and in polluted soils. They can serve as temporary measures after significant disturbances from fire to destructive winds. Human intervention can also be useful in cases where critical habitat-structures take many years to develop, such as the complex branch patterns and peeling bark in large old trees (Lindenmayer et al. 2013). For example, utility poles with additional structures can provide shelter, nesting sites, and perches while trees regrow (Hannan et al. 2019). Ecologists have found that such structures support mammals, birds, and insects.

2.3 How do prosthetic habitat-structures support or hinder cohabitation?

Prosthetic habitat-structures can complement urban design and planning measures geared towards cohabitation by integrating into building roofs or facades, infrastructure, parks and small greenspaces, or private gardens (Apfelbeck et al. 2020). Many organisms can adapt to human-implemented shapes and materials that are comparable to the structures with which they evolved (Sarkar and Bhadra 2022). However, the geometries, materials, and functions of human designs often differ significantly from historical analogues. Well-meaning interventions carry risk and can have unwanted consequences. Refuges, such as the hollows that form in trees over many years, illustrate the challenges. For example, artificial refuges can make animals more vulnerable to predation, overheating, parasites, and food shortages (Cowan et al. 2020; 2021). Human-provided hollows successfully attract some bird species but not all (Reynolds et al. 2019; Williams et al. 2013). There is a need for better design because nest boxes can have several negative effects on inhabitants and ecosystems (Zhang et al. 2023). For example, non-target animals such as honeybees sometimes take over certain nest box designs leading to nesting failure or low uptake from target species (Cunningham et al. 2022). Similar challenges are evident in other cases, such as bee hotels (MacIvor and Packer 2015). There is a widespread need for designs that function on par with baseline structures while remaining feasible to produce and maintain.

3 Challenges and opportunities for design research

Returning to my primary research question, how can design support multispecies cohabitation? I dissect this question into three parts: How can design (a) encourage beneficial relationships between human and nonhuman cohabitants; (b) produce better habitat structures; and (c) include nonhuman stakeholders as collaborators? I hypothesise that:

a) better knowledge of existing and possible cultures shared between human and nonhuman urban dwellers can help imagine paths toward multispecies cohabitation;
b) the use computer-assisted techniques can develop novel approaches to implementing and evaluating habitat structures; and
c) approaches to prototyping prosthetic habitat-structures for and with human and nonhuman stakeholders can cultivate persuasive proposals for multispecies cohabitation.

This thesis investigates these three hypotheses by adopting and extending approaches from state-of-the-art research and practice that recognise more-than-human capacities for culture, creativity, and collaboration.

3.1 Culture: Understanding cultures to imagine multispecies cohabitation

Design that considers interspecies cultures is necessary to achieve convivial cohabitation (Roudavski 2020). Interspecies cultures refer to the interactions and co-dependence of cultures shared between more than one species (Roudavski 2021). For example, human and other animals can share strong cultural connections to large old trees and learn to prefer certain prosthetic habitat-structure designs over others (Lindenmayer and Laurance 2016). Trees function as sites for communal living where complex behaviours, memories, traditions and cultures can involve humans, birds, bats, insects, and other nonhuman stakeholders (Roudavski and Rutten 2020). Encouraging mutually beneficial relationships where human and nonhuman cohabitants learn to live alongside each other requires research into what cultures already exist and imagination of what cultures might emerge through design.

3.2 Creativity: Using technologies to implement prosthetic habitat-structures

Technologies enable generation of innovative habitat-structures that would not be conceivable or practicable through human ingenuity alone. Technologies can be useful to develop artefacts that support living organisms through assisting observation and recording, modelling and simulation, form-finding, making, and monitoring (Zhou et al. 2022). For example, computer-aided design and manufacturing utilises technologies to enhance the geometric and material qualities of artificial habitat-structures tailored to target species (Watchorn et al. 2022; Cowan et al. 2021). Examples include 3D-printed reefs for fish (Levy et al. 2022), machine-milled façades for algae (Mustafa, Prieto, and Ottele 2021), perches for birds generated through artificial intelligence (Mirra et al. 2022), 3D-printed clay tiles on buildings for birds (Larikova et al. 2022), and complex seawalls that mimic mangrove forests, seagrass beds, and reefs colonised by coral and shellfish (Bishop et al. 2022). I have looked at how computer mapping and other tools can help humans to view cities through the lens of birds in order to generate better targeted design interventions (Roudavski and Parker 2020). Computer-aided workflows and decision-making tools can help deal with the complexity of designing building envelopes as shared places for animals, plants and microbiota by generating, evaluating, and selecting from multiple design options that integrate ecological knowledge (Selvan et al. 2023; Weisser et al. 2023). Technologies such as 3D scanning or algorithmic modelling can account for the complex behaviours of nonhuman organisms and the structures they create (Holland et al. 2023). Therefore, the work in this thesis explores ways to produce better prosthetic habitat-structures through prototyping that harnesses technologies for more than only human concerns.

3.3 Collaboration: Prototyping with nonhuman stakeholders to propose better designs

Design processes that involve and benefit nonhuman stakeholders is necessary to counteract human-centred design that results in increasingly diminished ecosystems (Roudavski 2021). Decision-making that recognises needs and capabilities of nonhuman organisms as participants is necessary to create more just, equitable cities (Pineda-Pinto, Frantzeskaki, and Nygaard 2022). The use of technologies can enable nonhuman stakeholders to have more of a say in design, as illustrated through smart systems that illuminate cities for humans while minimising the light pollution that affects other animals nearby, and panels with complex geometries that retrofit buildings or pavements for mosses and lichens (Roudavski 2020). Some projects also encourage organisms to take part in design through physical alterations, such as when spiders and caterpillars make their homes in human provided textiles (Keune, Dumitrescu, and Thomsen 2023) or when reintroduced beavers alter waterways in ways that benefit the wider ecosystem (Welden 2022). Despite growing theoretical arguments, nonhuman participation remains a methodological challenge in practice (van Bommel and Boonman-Berson 2022). This thesis develops tools and techniques to enrol nonhuman organisms as collaborators, with the aim of meaningfully translating their preferences into design.

4 Structure of the thesis narrative

The results of my PhD take the form of publications that consider the three aspects of more-than-human culture, creativity, and co-creation (Figure 1). This thesis develops novel design approaches through case studies and design experiments that focus on humans, owls, and other organisms that live in tree hollows. In particular, the powerful owl (*Ninox strenua*) serves as a useful case in several chapters. As apex predators, powerful owls indicate ecosystem health and regulate the numbers of other organisms such as possums (Buchanan, Wortham, and Powerful Owl Coalition 2018). Restoration of areas for owls can also benefit many other species (*ibid.*). Powerful owls are also a species that human find charismatic and culturally significant, which encourages support for habitat restoration and engagement in citizen science. These threatened birds are becoming increasingly common in cities, where they can find plenty of food but face numerous pressures from human activities (Cooke et al. 2018). A major issue is the lack of nesting sites. This is a problem for many other animals who similarly do not build nests and rely on hollows in old trees (Lindenmayer et al. 2012; 2013). In the case of powerful owls, Birdlife Australia reports that nest boxes have supported breeding in only two known cases. Design experiments are useful in this context because they do not only study the way systems are, but aim to intervene in ways that make improvements (Felson and Pickett 2005).

This thesis begins with a focus on design interventions for owls and then expands to other sites, species, and structures. The narrative begins by aiming to better understand patterns of existing and possible cohabitation to make urban design and policy recommendations, then puts these principles into practice by developing and testing workflows for implementing prosthetic tree hollows. The chapters investigate approaches to support multispecies cohabitation by:

1) addressing the challenges of human-animal conflict, coexistence, and cultural differences;
2) clarifying ethical implications of design and conceiving long-term visions for cities;
3) observing communities where multiple species successfully coexist;
4) prototyping prosthetic habitat-structures through innovative materials and technologies;
5) comparing prototype performance when supplied at large physical and temporal scales; and
6) developing tools that allow human and nonhuman stakeholders to co-create prototypes.

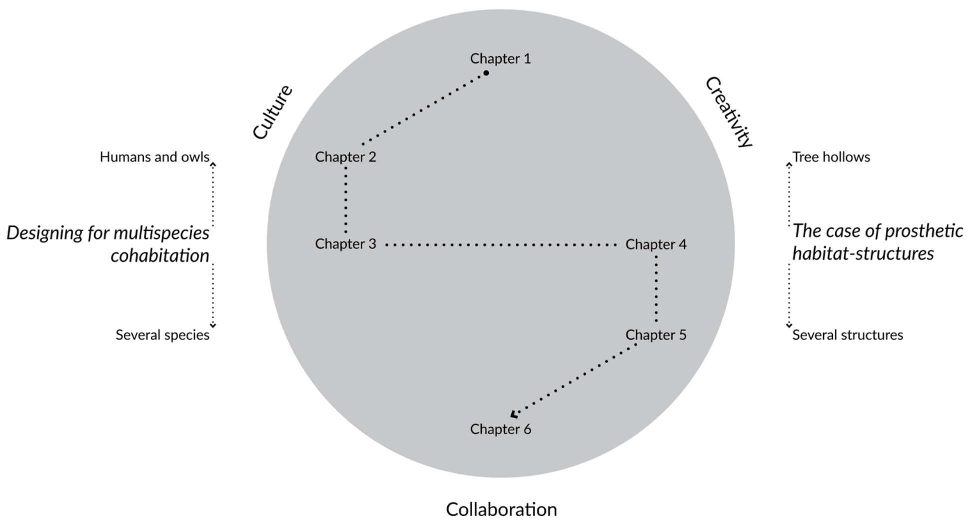

Figure 1. The structure of the thesis.

The structure of the chapters in this thesis is illustrated within the grey circle of Figure 1. The locations of the chapters within the circle indicate their focus.

- The chapters on the left side focus on understanding and proposing strategies for multispecies cohabitation.
- The chapters on the right side focus on the development and testing of prosthetic habitat-structures.
- The top-left section explores existing and potential interspecies cultures between humans and owls.
- The top-right section investigates the use of computer-assisted techniques to create prosthetic hollows.
- The bottom section examines ways to collaborate with nonhuman stakeholders in the design of prosthetic habitat-structures for various sites and species.

4.1 Chapter 1

Chapter 1 explores the tensions and opportunities of human-animal coexistence by developing a provocation in the form of prosthetic hollow design that considers the aesthetic preferences of owls. Published in a journal featuring art, science, and design collaborations, Chapter 1 provides considerations for interdisciplinary teams, including designers.

The design provocation helps explore how to design with nonhuman subjectivities in mind and identify how prosthetic habitat-structures might either intensify conflict or encourage coexistence. The chapter demonstrates that successful cohabitation depends on learning and adjustment from both humans and owls. For example, owls drop dismembered animal carcasses beneath roost trees, which some humans find repulsive. Conversely, large crowds of people may gather to catch a glimpse of these charismatic birds when they appear in urban areas, potentially disturbing the owls and causing them to exhibit abnormal behaviours. Additionally, more owls will impact other living beings; for instance, an owl might kill up to 300 possums per year.

These examples highlight the need to consider ethical issues when designing for cohabitation and to cultivate interspecies cultures that foster more beneficial relationships between humans, owls, and other nonhuman stakeholders.

4.2 Chapter 2

Chapter 2 addresses the need for an ethically justifiable and practically plausible framework for designing with and for nonhuman stakeholders. Published in a humanities journal with a multidisciplinary audience, this chapter offers tangible methods to include animals in urban decision-making and applies theories developed outside of design in innovative ways.

To support nonhuman participation in design, this chapter extends the capabilities approach to justice. The capabilities approach aims to ensure that living beings lead fulfilled lives. Like humans, nonhuman animals can flourish, and their lives can go well or badly. When a nonhuman animal cannot exercise a capability, the quality of its life diminishes. Beyond mitigating harm and risk, this chapter argues that design should aspire to create cities where nonhuman organisms are healthy and able to flourish in their own ways. Focusing on the powerful owl as a case study, this chapter develops a list of capabilities that account for owl health, autonomy, and relationships. Examples include owls' capabilities to roost, fly, hunt, play, and learn. The chapter considers how human-owl relationships might support or harm these capabilities; for instance, when humans use owls for entertainment or treat them as threats or annoyances. This method evaluates the capabilities of powerful owls in past, present, and potential future situations to establish goals for design. These goals include cultural shifts and retrofitting strategies to make urban structures more suitable for owls. Such proposals offer ambitious alternatives to the current forecasts that are bleak for owls.

Chapter 2 finds that understanding the capabilities of stakeholders is a productive way to involve nonhuman participants in design. It calls for comparisons between the ambitions to support capabilities and the realities of existing communities.

4.3 Chapter 3

Chapter 3 builds on the framework developed in the previous chapter by exploring cases of positive human-owl cultures through ethnographic fieldwork. Submitted to an interdisciplinary journal focused on eco-social issues, this chapter stands to benefit anyone who is interested in animal behaviour and seeks a better world for nonhuman cohabitants.

I interviewed people throughout south-eastern Australia who have committed considerable portions of their lives to living with owls. Most were semi-structured conversations while walking through urban areas where powerful owls live. These interviews documented nuanced and unpublished observations of owl behaviours, highlighting their emotional bonds with family members, ability to manage food resources in novel ways, and express themselves in a range of situations. The recognition of these abilities can inform human behaviours and urban developments that better accommodate their rich inner lives. The chapter demonstrates that beneficial interactions are possible and can be supported by human-made habitat structures. Such instances of successful cohabitation offer a hopeful vision of urban living, characterised by mutual respect, understanding, and support.

These findings outline useful steps toward cohabitation, offering managers, planners, and policy makers recommendations for urban transformation and research. The exploration of interspecies cultures in this chapter underscores the importance of creating biodiverse and equitable urban environments, supported through the development of prosthetic habitat-structures that better account for the complex behaviours and interactions of organisms.

4.4 Chapter 4

Chapter 4 developed workflows that use computer-aided approaches to improve the design of prosthetic hollows. Published in an ecological journal, this chapter offers reusable approaches to help conservationists address the shortcomings of existing designs such as nest boxes.

Rather than starting with a box, the design process starts by looking at behaviours of target species and their usual nesting structures. Owls, for example, often nest in large old tree hollows and termite nests. Computer-aided design and manufacturing helps generate prosthetic habitat-structures that match the properties of these nesting sites. The resulting prototypes, made of 3D printed wood and hempcrete, are installed in Melbourne, Australia.

From field testing side by side with existing designs across a range of criteria, this chapter found that computer-assisted techniques result in benefits for multiple human and nonhuman stakeholders, including ecologists, land managers, arborists, and birds. These include geometries that resemble complex characteristics of tree hollows, materials that are biologically derived and thermally stable, and structures that are lightweight and easy to install.

The workflow is broadly applicable to different sites and species, and can assist in the deployment, testing, and selection of better designs. The capacity for adjustment and continual improvement allows designs to better respond to specific contexts, making cohabitation more feasible.

4.5 Chapter 5

Chapter 5 builds on the previous chapter by establishing novel methods for supplying prosthetic hollows as persistent and long-term services. Submitted to an ecological journal, this chapter offers land managers a way to select the most suitable designs for specific sites that require human supplied hollows.

Chapter 5 introduces a lifecycle approach to fill knowledge gaps that constrain innovation and make it difficult to understand the environmental impact of wide-scale installation. The approach enables novel designs based on the biological cycles of tree hollows and assesses the sustainability of options using technological lifecycle analyses. To test the approach, the chapter models the long-term implications of reinstating nesting sites at an area in Trentino, Italy, where a storm in 2018 toppled large areas of forest. The chapter compares prototypes made from laser-cut plywood, 3D-printed plastic, and mycelium blocks assembled using augmented reality. It forecasts the environmental impacts of each prototype across multiple generations, taking into account the need to replace installations at the end of their lifespan. The analysis includes estimates of upfront and long-term carbon emissions, energy use, costs, and waste production over 50 years, which approximates the amount of time human-supplied hollows will be necessary until trees become large enough for woodpeckers to begin supplying hollows again.

The modelling in this chapter can support better design decisions because it reveals the cumulative advantages and disadvantages of different designs over time. Decision makers can use such information to estimate the consequences of deploying hollows across large areas and quantify the benefits of selecting the most sustainable design option over the cheapest one. Chapter 5 confirms that design choices can lead to significant environmental impacts, providing evidence that could help to advocate for better preservation of forests, or to demand more from developers who are providing inadequate offsets.

4.6 Chapter 6

Chapter 6, the final chapter of this thesis, assembles the approaches from previous chapters into a toolkit that aims to make innovative design more accessible. Presented at a conference centred on sustainability in the built environment, this chapter brings the benefits of computer-aided design to community-led conservation initiatives where residents, councils, and conservationists create and monitor habitat structures.

To do this, Chapter 6 develops a proof-of-concept website that allows anyone with an internet connection to customise prosthetic hollows to suit their unique circumstances. Website users can adjust designs to match requirements of different sites, management needs, target species, or personal circumstances such as budget, time constraints, and available materials. The chapter discusses a public workshop to test the configurator, involving students, Indigenous rangers, volunteers in environmental initiatives, and residents. This trial shows how online toolkits for prosthetic habitat-structures can create novel opportunities to support knowledge sharing and innovation.

Through such engagements, citizens can learn about more novel technologies and their local ecosystems. At the same time, their participation helps to improve processes in ways that can lead to better designs and widespread implementation. Significantly, Chapter 6 demonstrates the potential for online toolkits to translate local knowledge and expertise of human and nonhuman stakeholders into the shapes and materials of prosthetic habitat-structures.

These chapters come together to provide an understanding of how design can help to achieve cohabitation.

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Chapter 1. Toward Interspecies Art and Design: Prosthetic Habitat-Structures in Human-Owl Cultures

Dan Parker, Stanislav Roudavski, Bronwyn Isaac, and Nick Bradsworth

Abstract

Urbanisation severely reduces opportunities for nonhuman habitation and undermines nonhuman subjectivities, aesthetic experiences, behaviours, traditions, and cultures. In response, humans need to reimagine cities as places for multispecies cohabitation. A team of architects and ecologists, we demonstrate that such reimagination depends on cultural behaviours of multiple species and illustrate the implications of this dependence by designing and discussing nesting structures for the powerful owl (Ninox strenua). The project shows that prosthetic habitats can serve as a useful provocation for thinking about interspecies cultures and opens productive avenues for further research.

1 The interspecies art hypothesis

1.1 Multispecies cohabitation

Disturbances caused by people, buildings and traffic make cities inhospitable to many nonhuman species. Yet even the densest megapolises provide habitats for nonhuman organisms as well as for humans (Lowry, Lill, and Wong 2013). Such urban cohabitation can cause conflict between human and nonhuman dwellers. For example, human activities can disrupt nonhuman animals' behaviour, breeding, and foraging. Conversely, nonhuman animals can damage property, attack humans, spread disease and increase dirtiness or noise (Soulsbury and White 2016). Despite such challenges, it is important to enhance cultural diversities in urbanised environments. This diversification is important because nonhuman lifeforms can benefit from acculturation to human-modified habitats and humans—from accommodating behaviours and traditions of other organisms.

1.2 Interspecies culture

To describe more-than-human cultural interactions, this article proposes the notion of *'interspecies culture'*. Interspecies cultures emerge when cultures of more than one species become co-dependent. This notion presumes a definition of 'culture' that includes nonhumans. Traditional humanist positions (cf. Charles Ellwood, Edward Tylor, Franz Boas, Clark Wissler, Robert Lowie or Alfred Kroeber) understand culture as a uniquely human achievement. However, recent research demonstrates that nonhuman lifeforms also engage in forms of culture that are important for their wellbeing and survival (Brakes et al. 2021). Such cultures obtain, for example, in foraging tactics, predator avoidance, vocal communication, habitat use, breeding-site choices and play (Whiten et al. 2017). Nonhuman cultures emerge through socially transmitted information that includes behaviours, traditions, beliefs, knowledges, skills and practices (Mesoudi 2016). We suggest that curated interactions between such cultures can foster solidarity and understanding among all urban dwellers (Roudavski 2020; 2021).

1.3 Interspecies art and design

How can cities support interspecies cultures and shape them to encourage mutually beneficial cohabitation? Cultures can have multiple expressions via shared behaviours, rituals, customs, ethics, objects and art. This article focuses on the aesthetic dimensions of culture. We introduce the idea of *'interspecies art'* to describe one type of activities that promote interspecies cultures. Production of such art depends on an understanding of aesthetics that acknowledges nonhumans' ability for aesthetic judgments. Female bowerbirds or peahens make such judgements, for example, when selecting mates (Prum 2013). This more-than-human understanding of aesthetics can invite humans to rethink familiar concepts, practices and sites in ways that highlight presences and roles of nonhumans. We frame such re-conceptualisations as art. In its attention to evidence, participation and orientation towards practical outcomes, such art is similar to approaches that include 'public art', 'social art' and 'useful art' as well as 'speculative design', 'transition design' and 'design as activism'. To provide a working definition, *interspecies art consists of aesthetic practices that are 1) produced and 2) used by more than one species*. Explicit inclusion of nonhumans into the use of art distinguishes our understanding from the existing interpretations of interspecies art. They are different because these existing interpretations commonly presume that outcomes of art will make sense in human cultures and will be appreciated and used by humans (Ullrich 2019).

This article extends these approaches by exploring and highlighting cultural implications of art for more than one species. It hypothesises that interspecies approaches to culture, art and design can usefully inform practices of urban cohabitation. We aim to illustrate the feasibility of such approaches by providing examples of solvable problems and listing directions for further research.

One way to produce interspecies art is via design experiments. Such experiments can combine scientific knowledge with iterative approaches towards creative production. We illustrate this approach through a consideration of prosthetic habitat-structures. The term 'prosthetic habitat-structures' refers to artefacts that aim to reinstate absent habitat opportunities by grafting remedial elements onto existing structures. The process of specifying proposals for such habitats can benefit from the enrolment of all stakeholders, human and nonhuman. We call this practice *'interspecies design'*. The development of effective methods for such design is an open challenge. For example, design collaboration with nonhuman lifeforms is nontrivial because they cannot describe their needs in human languages.

Our methods contribute to the construction of theory and the advancement of practice by exploring the issues highlighted by a design provocation. This approach depends on the selection of an appropriate case. Here, we choose to focus on: 1) the challenge of dwelling; 2) on dwelling supported by habitat structures; and 3) on the challenge of replacing naturally occurring habitat structures with human-made objects. Lives of many species in all biomes depend on these steps, making our confined case representative of widespread phenomena.

Our case study provides technical recipes for the construction of prosthetic habitat-structures and a comparative assessment of habitat designs (see supplementary materials). However, these aspects of the project are beyond the scope of this article. Instead, we focus on overlapping cultural concerns to 1) outline owls' culture in relationship to humans; 2) outline human cultures in relation to owls; and 3) illustrate relevant human-owl cultural issues in application to interspecies design.

2 The case of powerful owls

To explore how prosthetic habitat-structures can encourage interspecies cultures, we focus on one species, the powerful owl (*Ninox strenua*) (see supplementary materials). Powerful owls live in eastern and south-eastern Australia. They are threatened in the southern parts of their range (Department of Environment, Land, Water and Planning 2019), where humans have significantly reduced the number of large old trees that owls use for nesting.

In response, our project analyses owl biology, ecology, and behaviour to propose innovative interventions that can convert existing urban structures into owl homes. To date, this ongoing long-term project has installed and is monitoring several prosthetic nests (Figure 1). We continue the assessment of ecological outcomes, but these aspects are beyond the scope of this article, which focuses on culture and design.

Figure 1. A prosthetic-nest prototype installed in a living tree.

2.1 Human cultures

Human-owl cultures have long and varied history. Humans fear and admire owls, associating them with wisdom, power, clairvoyance, good (or bad) omens, mystery, death and medical cures (Morris 2013). Humans use owls as subjects of art, architecture, literature, films, toys, banknotes, and institutional logos (see examples in Morris 2013). The public might learn some owl-related facts through these cultural means but general knowledge about specific owls in specific places is varied and often limited (cf. Mikkola 1997; 2000; Torkar et al. 2019). Humans might sometimes experience urban owls as exciting curiosities but otherwise have few occasions to consider their lives. This detachment is problematic as urbanisation continues to force more owls into cities, increasing potential for interspecies conflict (Boal and Dykstra 2018). For instance, owls do not clean their nests and leave dismembered animal carcasses under nest sites (Figure 2). In dense cities, humans might find resulting smells and sights repulsive.

Human ignorance about owls' needs can lead to harmful practices (Mikkola 1997; 2000). For example, urban managers removing understory vegetation can be problematic (Buchanan, Wortham, and Powerful Owl Coalition 2018). Owl chicks that fledge in the areas without such vegetation to protect them from hard landings can suffer injuries and the disturbance of clearing might cause them to fledge prematurely (Hannam 2018). Further harm results from other disturbances. Powerful owls are charismatic and reported sightings can attract many observers (Figure 2). Human presence can force owls to abandon their nests and exhibit other abnormal behaviours, possibly including infanticide (Webster et al. 1999). Such examples demonstrate that owls will not succeed in urban areas without a shift in human cultures. Better familiarity with owls' life histories is likely to result in greater empathy, solidarity, and practical support.

Figure 2. Potential conflict between humans and owls. Left: a powerful owl roosting with dismembered prey (Photo: Nick Bradsworth 2017). Right. crowds gather to watch a powerful owl in an inner-urban context (Carlton, Melbourne) (Photo: Lian Hingee 2016).

2.2 Owl cultures

Owls also must adapt their behaviours to prosper in urban conditions. Their ability to engage with new objects and develop new habits indicates that this is feasible. Environmental change, including introduction of human-made structures, can lead to the emergence of new cultures in many species, including cetaceans, birds and primates (Whiten 2021).

With owls, evidence suggests that juveniles can learn from adults through mimicking. Examples of young owls copying their parents' hunting strategies include snatching at branches to capture insects, ferrying bark strips, chasing aerial fauna and swooping animals on the ground (Mo and Waterhouse 2015). Birds adhering to distinct musical trends in different regions provide an example of cultural variation within one species (Aplin 2019). Urban owls show similar capabilities when they learn to be more tolerant of humans compared to their bush-dwelling conspecifics (Mo et al. 2016).

Owls can also be inventive as individuals. They use arboreal termite mounds (Figure 3) and non-native trees for nesting. Their roosting choices can include tennis-court fences and power lines. They exhibit atypical behaviours such as catching fish (Mo, Hayler, and Hayler 2016) and practice hunting techniques on clothing, cooler bags and towels (Figure 4). This plasticity can be dangerous and owls in human-altered places suffer from car-strikes, disease, electrocution, entanglement and fluctuating prey populations (Bain et al. 2014). By contrast, their flexibility suggests the potential for cultural adaptation to novel ecosystems.

Figure 3. Atypical nesting sites. Left: a powerful owl chick nesting in a termite nest (Photo: Ofer Levy 2017). Right: an arboreal termite mound (Photo: Richard Jackson 2012).

Figure 4. Powerful owls exhibiting novel behaviour with human-made items. Left: a powerful owl with a cooler bag. Right: a powerful owl pair with a tea-towel (Photo: Choosypix 2015).

3 Interspecies-design experiment

Following a glimpse into human-owl interactions, we continue with the introduction into the case-study design provocation and its cultural implications.

Existing provisions for owls include nest boxes, hollows from felled trees and even repurposed waste bins (Figure 5). To date, there is only one observation of a successful powerful-owl breeding in a nest box and only one of the two chicks survived (McNabb and Greenwood 2011). The rectilinear forms of plywood nest boxes do not match material and geometric complexity of the natural structures they aim to replicate. Current techniques result in structures that could benefit from functional and cultural improvements. For humans, they can be heavy and difficult to install (Figure 6). For owls, they can be too hot and appear too unfamiliar for consideration during nest-site selection.

Figure 5. Existing nest designs for the powerful owl. Left: a repurposed wheelie-bin nest (Photo: Gio Fitzpatrick 2016). Right: a nest box (Photo: Ed McNabb 2011).

Figure 6. Installation of log hollows. Left: an arborist installing the log into place at a tree crotch. Right: arborists hoist a heavy log up the host-tree.

Our project uses algorithmic modelling to generate forms informed by arboreal termite mounds. Such mounds can self-organise to fit existing living, dead or human-made structures. The project also generates forms that can fit these locations. These forms aim to support owls' nesting habits. For example, designs provide rounded edges that suit the owls' large talons during landing. Inside, there are platforms for feeding the chicks and roughened interior surfaces for scratching and climbing (Figure 7). For further details on the generative techniques, refer to the supplementary materials and Roudavski and Parker (Roudavski and Parker 2020).

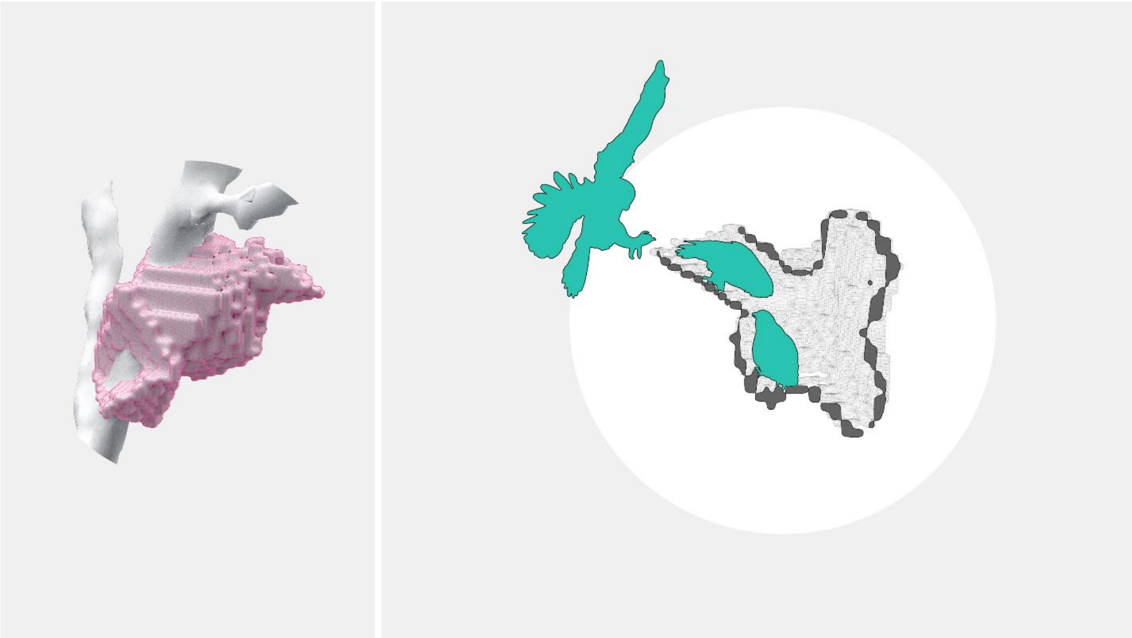

Figure 7. Computational design of prosthetic nests for the powerful owl. Left: a model wrapped around the unique form of a dead tree. Right: functional features, including a rounded entrance for landing, an entrance pad for feeding and a roughened interior for scratching.

4 Discussion and future work

How can such interspecies approaches to culture, art and design inform urban cohabitation? We respond to this question by highlighting cultural implications of prosthetic habitats. First, we position prosthetic habitat-structures as art and identify future practical work. Second, we introduce issues for future research into human-powerful owl cultures in the context of such design. Last, we raise important questions for future cohabitation that emerge whenever prosthetic habitat-structures attract new tenants.

4.1 Prosthetic habitat-structures as interspecies art and design

We propose seeing designs of prosthetic nests as artistic expressions that are meaningful in relevance to the cultural needs of owls. Owls must recognise and approve the resulting artefacts before attempted use and find them agreeable in practice. Successful design will have to consider pragmatics and aesthetics of both human and owl cultures. Further, prosthetic habitat-structures will need to refer to owls' subjective expressions and not only to generic bodily requirements or species-wide considerations. In turn, owls might learn to recognise, accept, and use locations and forms that are increasingly different from ancestral templates, extending their capacity to inhabit novel ecosystems.

Future work should make improvements to prosthetic nests' geometry, material, and construction in ways that extend engagement with the subjective preferences of humans and owls. For instance, owls may benefit from the intelligent distribution of material properties such as locally soft, porous, and self-repairing surfaces. Such features are common in natural hollows with decomposing floors that are safe for the eggs and regrowing edges that resist scratching. Simultaneously, humans may want to participate in the design and making of prosthetic nests that benefit local ecologies while adhering to their cultural values.

4.2 Prosthetic habitat-structures in interspecies cultures

Such improvements to design and management will rely on further research into human attitudes towards owls and owl cultures. Better knowledge of the existing and possible interspecies cultures can help to address the challenges of cohabitation. For instance, should prosthetic habitat-structures for owls be visible to humans or kept in secret? On one hand, future management can aim to capitalise on owls' cryptic lifestyles and keep their behaviours hidden from humans. However, if owls remain hidden, the 'extinction of experience' (Soga and Gaston 2016) where humans have no contact with nonhuman lifeforms, will only increase. This type of extinction is unhealthy for humans and can lead to the loss of support for nonhuman lives. Complete isolation desired by some activists will likely be unfeasible for many species that cannot escape or choose to live in cities. A compromise might make owls visible but not disturbed, acculturated to urban life but not tamed.

Any future management will have to take cultural implications of such options into account. Researchers will have to conduct further investigations on foraging patterns, home-range areas, and dispersal of young adults to inform these choices. Such research ought to engage with multiple knowledges, including community experiences and anecdotal observations, scientific evidence, indigenous expertise, and fictional narratives.

4.3 Prosthetic habitat-structures and multispecies cohabitation

Regarding future cohabitation, our case-study shows that design provocations can generate useful challenges for further experimentation with interspecies relationships. Cohabitation of humans and nonhumans produces novel cultural attitudes. Such attitudes are a subject of ongoing contestation because they depend on moral and political preferences as well as on bodily or cognitive capabilities. Management of such tensions will determine whether human-made habitat structures will be built, last or prove successful.

Should owls become like pigeons and sparrows or even like pets? On one hand, urban adaptation of species such as pigeons can cause over-habituation, overabundance, and frequent human-wildlife encounters. A significant repercussion of such encounters is the popular disdain towards common species and consequent efforts to remove them from cities (Jerolmack 2008). Conversely, keeping owls as pets will prevent them from expressing their capabilities, such as choosing partners or deciding on roosting sites. For example, after the release of the Harry Potter films in Indonesia, owls became popular as pets. This resulted in the proliferation of illicit capturing, trading and subsequent abandonment (Nijman and Nekaris 2017). Large-scale human help can also lead to problems. For example, globally, birds already rely on human-made structures (Mainwaring 2015). This is potentially problematic because humans can favour some species leading to the demise of others, or create dependences on human-made structures without guarantees of continuing support. Future decision-making on human-owl relationships may benefit from design that tests possible future states at various temporal and physical scales.

5 Conclusion

This article demonstrates that design of prosthetic habitat-structures can highlight issues of interspecies cultures and indicate directions for further research. To inhabit human cities, owls need to become more tolerant of disturbance and human-made objects. At the same time, humans must learn more about the habits of owls and adjust their attitudes. Such mutual shifts are necessary in many other situations and for many other species. As in other intercultural engagements, best practices are likely to emerge when stakeholders will influence decisions as active agents and not only as passive recipients of care.

6 Supplementary materials

For published article and supplementary materials, see:
https://doi.org/10.1162/leon_a_02224

7 Author contributions

Dan Parker led the writing, developed the designs, and produced the images. Stanislav Roudavski conceptualised the overarching ideas and assisted with writing and image production. Bronwyn Isaac and Nick Bradsworth provided ecological advice, fact checked the article, and helped edit the writing.

8 Acknowledgements

This project was supported by the Australian Research Council Discovery Project DP170104010.

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Chapter 2. Interspecies Cultures and Future Design

Dan Parker, Kylie Soanes, and Stanislav Roudavski

Abstract

This article introduces the notion of interspecies cultures and highlights its consequences for the ethics and practice of design. This discussion is critical because anthropogenic activities reduce the abundance, richness, and diversity of human and nonhuman cultures. Design that aims to address these issues will depend on interspecies cultures that support the flourishing of all organisms. Combining research in architecture and urban ecology, we focus on the design of urban habitat-structures. Design of such structures presents practical, theoretical, and ethical challenges. In response, we seek to align design to advancing knowledge of nonhuman cultures and more-than-human justice. We present interspecies design as an approach that incorporates human and nonhuman cultural knowledge in the management of future habitats. We ask: what is an ethically justifiable and practically plausible theoretical framework for interspecies design? Our central hypothesis is that the capabilities approach to justice can establish goals and evaluative practices for interspecies design. To test this hypothesis, we refer to an ongoing research project that aims to help the powerful owl (Ninox strenua) thrive in Australian cities. To establish possible goals for future interspecies design, we discuss powerful-owl capabilities in past, present, and possible future situations. We then consider the broader relevance of the capabilities approach by examining human-owl cultures in other settings, globally. Our case-study indicates that: 1) owl capabilities offer a useful baseline for future design; 2) cities diminish many owl capabilities but present opportunities for new cultural expressions; and 3) more ambitious design aspirations can support owl wellbeing in cities. The results demonstrate the capabilities approach can inform interspecies design processes, establish more equitable design goals, and set clearer criteria for success. These findings have important implications for researchers and built-environment practitioners who share the goal of supporting multispecies cohabitation in cities.

1 Introduction

This article considers the notion of interspecies culture and highlights its consequences for the ethics and practice of design. These considerations are particularly important in the context of urban, landscape, and architectural design but are also applicable to other activities that plan for and work to implement better futures. To explore this topic, we investigate how design can respond to advancing knowledge on nonhuman cultures and more-than-human justice. This discussion is critical because anthropogenic activities reduce the abundance, richness, and diversity of all cultures, human and nonhuman (Gruber et al. 2019). Unfortunately, design is responsible for much of this damage. Design that aims to address these issues will depend on interspecies cultures that support the flourishing of all organisms. As a starting point, we present an approach that integrates cultural knowledge of multiple species. Combining research in architecture and urban ecology, we focus on urban habitat-structures (see Roudavski 2020). This work addresses the urgent need to provide habitat that supports human and nonhuman cohabitation in cities. [1] Design of such structures presents practical, theoretical, and ethical challenges. Engaging with these challenges, we ask: what is an ethically justifiable and practically plausible theoretical framework for interspecies design? To address this question, we discuss conceptions of justice that include human and nonhuman beings. We hypothesize that the capabilities approach can establish goals and evaluative practices for interspecies design. To test this hypothesis, we refer to an ongoing research project that aims to help the powerful owl (*Ninox strenua*) thrive in Australian cities. Using this project as a characteristic example, we discuss past, present, and future communities of humans and owls, highlighting the impact on the wellbeing of individuals and ecosystems. Our analysis contributes to scholarship by reconsidering conservation in response to interspecies knowledge and testing ideas of justice in application to design.

1.1 Interspecies cultures

Discourse within environmental humanities provides relevant background to our notion of interspecies cultures. This discourse interrogates relations that involve all life on earth (Rose et al. 2012). The 'multispecies turn'—also known as the 'nonhuman', 'animal', or 'more-than-human' turn—challenges ontological distinctions between nature and culture, human and nonhuman, and subject and object (Locke 2018). [2] Discourses of new materialism, posthumanism, actor-network theory, and feminism also discuss the abandonment of such dualisms (Haraway 1991; Coole et al. 2010; Braidotti 2019; Latour 2007). Significantly, these studies move away from human exceptionalism, recognising the interdependencies and entanglements of human and nonhuman entities. Multispecies studies aspire towards more diverse, rich, and autonomous ways of living together (Collard, Dempsey, and Sundberg 2015).

[1] Relevant fields include urban planning, urban design, landscape architecture, and architecture (Parris et al. 2018; Garrard et al. 2018; Grose 2014; Felson 2013).

[2] This turn engages philosophy, anthropology, geography, art, cultural studies, literary studies, and history, among others (Van Dooren, Kirksey, and Münster 2016). These fields also include design, planning, and sustainability (Houston et al. 2018; Rupprecht et al. 2020).

In keeping with this objective, we aim to understand interests and experiences of others, recognising nonhuman knowledge, consciousness, intelligence, creativity, emotions, personality, intentions, and desires (Celermajer, Schlosberg, et al. 2020). Such understandings are useful to conceptualise human responsibilities towards other beings of all kingdoms. Extending this discourse, we begin by outlining the need for human cultures that support the flourishing of other taxa. Following, we introduce how cultures emerge in nonhuman animals and outline the potential to cultivate interspecies cultures.

1.1.1 Human cultures

Without innovative modifications of prevalent human practices, the unfolding environmental crisis is likely to grow catastrophically, provoking unstoppable climate change, global-scale ecosystem collapse, and the destruction of human and nonhuman lives (Masson-Delmotte et al. 2021). Even where species still survive, their ecological interactions may be effectively extinct (Valiente-Banuet et al. 2015). The loss of interaction with other lifeforms and associated decline of human ecological knowledge, or the 'extinction of experience', will make the reversal of these trends increasingly difficult (Soga and Gaston 2016). Resulting 'shifting baselines' for conservation can occur as the perceived condition of ecosystems changes over time due to the loss of knowledge about past conditions (Papworth et al. 2009). Consequent injustices arise through human-induced homogenisation of species, languages, and cultural habits (Rozzi 2013). Biodiversity, endangered species, and extinction are cultural narratives that frame human perceptions of, and engagement with, nonhumans (Heise 2016). Human worldviews, stories, media, scientific studies, livelihoods, norms, and institutions reflect and influence relations among plants, humans, and other animals (Elands et al. 2019). Recent scholarship calls for conservation practices to account for human-cultural differences, engage with local communities, and incorporate social narratives on multispecies histories, locality, and Indigenous forms of knowledge (Straka et al. 2018; Taylor et al. 2021; Aisher and Damodaran 2016). These cultural aspects have important implications for species conservation and human-wildlife conflict (Soulsbury and White 2016; Schuetz and Johnston 2019).

1.1.2 Nonhuman cultures

Culture is not unique to humans and research on nonhuman cultures is expanding in several fields. Recent reviews of biological literature demonstrate that many nonhuman animals have culture (Brakes et al. 2019; Whiten 2021). Acknowledgements that culture is not unique to humans have also become more common in the humanities and social sciences. [3] Understood as the transmission of socially learned behaviours, culture is important for wellbeing and survival (Brakes et al. 2021; Brakes 2019). Cultures influence migration patterns, communication, food selection, foraging strategies, breeding-site choices, courtship and mating, play, habitat use, and risk avoidance (Whiten 2021). Examples of cultural expressions include place-specific dialects of genetically identical birds, socially learned songs of whales, and regional use of tools by chimpanzees (Aplin 2019; Whitehead and Rendell 2014; Safina 2020). Anthropogenic activities can alter or destroy such cultures. For instance, extensive land

[3] There are also examples in geography, sociology, and post-colonial studies (Hodgetts and Lorimer 2015; Nimmo 2012; Corman 2020).

clearing in Australia led to endangered honeyeaters losing their songs and even adopting the songs of other birds, thereby making the males less attractive to females (Crates et al. 2021). Novel conservation responses attempt to restore lost cultures, for example through the use of drones to teach ibis cranes their forgotten migratory flightpaths (Sperger, Heller, and Voelkl 2017). A significant challenge is to preserve existing relationships while also imagining and permitting new cultures that involve human and nonhuman cohabitants.

1.1.3 Development of shared cultures

We see this situation as an opportunity to cultivate interspecies cultures which curate non-anthropocentric interactions and foster beneficial relationships between humans and nonhumans. This is possible because both human and nonhuman animals continually reconstruct their cultures. Cultures develop across generations, emerging as beliefs, knowledge, skills, traditions, or practices (Mesoudi 2016). Behavioural plasticity and innovation allow animals to adjust their behaviour to suit local conditions such as those found in cities. As an example where humans taught birds novel foraging techniques demonstrates, such cultures are influenceable and can spread rapidly throughout populations (Aplin et al. 2015). The ability to acquire new cultures presents opportunities, but also carries risks. On one hand, cultural adaptation can help animals to adjust their behaviours in response to changing environments (Brakes et al. 2021). On the other, cultures can prevent the spread of adaptive behaviours or lead to detrimental consequences (Prum 2017). Individuals can copy behaviours that result in harmful cultures (Aplin 2019). Further, there may be a risk that humans continue to dominate the development of new cultures. In constructing their own niches, humans profoundly alter habitats and therefore cultures, behaviours, populations, wellbeing, and even evolution of species (Alberti et al. 2020). Highly human-altered ecosystems can intensify evolutionary traps, where population declines occur because animals make maladaptive selections of habitats, mates, food, or other resources (Robertson, Rehage, and Sih 2013). Human social patterns and culturally informed activities alter evolution in urban environments and require design strategies that can facilitate adaptations to urban habitats instead of attempts to restore historic conditions (Roches et al. 2021; Rivkin et al. 2019).

1.2 Interspecies design

1.2.1 Nonhuman knowledge

We argue that designers ought to develop intentional engagements with interspecies cultures. Design, as a process that shapes futures and impinges on existing ecosystems, will play an important role in imagining new shared cultures. Interspecies design provides an opportunity for this endeavour. Understood as an approach to the management of future habitats, interspecies design entails a process of deliberate designing ***for*** or ***with*** more than one species (Roudavski 2021). Potential applications of interspecies design range from small objects, products, or graphic visualisations to urban landscapes, systems, or fictional worlds. Our own research focuses on physical structures that support human and nonhuman cohabitation. Examples include small-scale habitat-structures for bees, building-scale attachments for mosses, tree-scale interventions for vertebrates, and landscape-scale schemes for parklands and ecological infrastructure (Roudavski 2020) These projects move away from the prevailing approaches of design for nonhumans which remain anthropocentric and seek to satisfy human criteria for success (Roudavski 2018). For instance, contemporary design projects create pavilions that exploit animals for artistic labour and structures that position animals as livestock for human consumption (Wolch and Owens 2017). Yet non-anthropocentric forms of design are on the rise (DiSalvo and Lukens 2011). Some of these approaches seek to involve nonhumans in design processes without exploitation or forced adjustment to human lifestyles (Rosińska and Szydłowska 2019; Forlano 2017; Westerlaken and Gualeni 2016).

Going further, designers can grant nonhumans goal-setting and decision-making powers, and therefore abilities to influence the outcomes of design processes (Veselova and Gaziulusoy 2019). Nonhumans possess knowledge and perspectives that could offer valuable contributions to the design of future environments. Many nonhumans alter their environments through interspecies interactions and cultural expressions, such as nest building or ecological engineering of dams (Breen 2021; Barker and Odling-Smee 2014). Even organisms that do not construct their own habitat structures have agency that includes abilities to act, bring about change, and affect others (Räsänen and Syrjämaa 2017). Attempting to incorporate such knowledge presents significant opportunities for future interspecies design that benefits nonhumans.

1.2.2 Ethics and design

Integrating nonhumans into design processes presents unresolved ethical challenges. Namely, existing design ethics concentrates on human interests (Chan 2018). In response, we consider ethical aspects of interspecies cultures and design. Any design undertakings must make ethical judgements on aesthetics, values to prioritise, and trade-offs to make (Lagueux 2004). Therefore, designers ought to consider possible consequences of their designs when they attempt to improve existing situations (Fry 2004). In the context of interspecies design, humans are in an exceedingly powerful position. Research on cultural ecosystem-services remains largely anthropocentric but provides insights into potential challenges. It considers approaches to preservation of cultural values, incorporation of diverse worldviews into decision-making, and integration of multiple disciplines into deliberation processes (Gould, Morse, and Adams 2019; Cabana et al. 2020). Responding to these challenges, we ask: what is an ethically justifiable and practically plausible theoretical framework for interspecies design? Our central hypothesis is that theories of justice can provide useful frameworks for designing future environments that support interspecies cultures. Although justice is a disputed term that has many different interpretations, its more-than-human conceptualizations offer insights into ways of balancing human, non-human animal, and even non-sentient interests (Hickey and Robeyns 2020; Biermann and Kalfagianni 2020). Notably, 'multispecies' and 'interspecies' justice seek to recognise experiences and interests of all living beings and provide a pragmatic frame to consider related ethical issues (Plumwood 2002; Celermajer, Chatterjee, et al. 2020; Celermajer, Schlosberg, et al. 2020). [4] Similar to multispecies approaches, interspecies justice emphasises the co-presence of many forms of life but puts emphasis on their relationships

[4] For the discussion of similar issues without the use of the term 'interspecies', see (Armstrong 2013).

(Bosselmann 2006; 2008). This focus allows us to consider cultures in living forms, especially in animals. [5]

2 Methods

2.1 Capabilities as design criteria

We investigate ideas of justice for interspecies design through the notion of capabilities. The capabilities approach to justice aims to ensure that living beings have fulfilled lives. Its early interpretations supported evaluations of human wellbeing beyond the narrow notion of economic welfare (Robeyns 2009). Capabilities referred to the opportunity for a human or a group of humans to achieve what they value (Sen [1999] 2015). More recent literature extends the capabilities approach to sentient animals (Nussbaum 2007; Tulloch 2011). Like humans, nonhuman animals can flourish and their lives can go well or badly (Cripps 2010). When a nonhuman animal cannot exercise a capability, the quality of their life diminishes (Fulfer 2013). Extending beyond the utilitarians' focus on sentient animals' capacity to feel pleasure and pain, the capabilities approach seeks to account for cognitive and social lives of animals (Nussbaum 2011). Going beyond the contractarians' focus on compassion and humanity, this conception of the capabilities approach treats animals as subjects with agency (Schinkel 2008). More inclusive understandings of the capabilities approach account for cultural groups and systems such as rivers or forests (Schlosberg 2007: 148). These approaches argue that harm to sentient or non-sentient organisms may hinder their capabilities for flourishing. [6] Case-studies on stormwater systems and urban forests demonstrate the usefulness of the capabilities approach to integrate human and nonhuman stakeholders into design and decision-making (Heikkinen et al. 2019).

2.2 The powerful owl as a case-study

We test the capabilities approach in the context of an ongoing project that aims to help large owls thrive in or around cities. Our component of the project focuses on the design of habitat-structures for the powerful owl (*Ninox strenua*), a threatened species in south-eastern Australia. [7] We conduct this project in the context of a broad effort by multiple parties to

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[5] We acknowledge that biocentric justice is but one of the aspects of ecocentrism, along with such frameworks as geocentric ethic and astroethics. Bosselman understood interspecies justice as a concern for the nonhuman world and defined ecological justice as consisting of three elements: intragenerational justice, intergenerational justice, and interspecies justice. We focus on interspecies justice for pragmatic reasons. This focus allows us to focus on the considerations of cultures that are more readily acceptable in living forms, especially in animals. Broader discussions of universal considerability are important but remain outside of scope for this article.

[6] We acknowledge the potential limitations and critiques of the capabilities approach, including its possible intersections with anthropomorphism, individualism, universalism, and paternalism. However, the potential benefits to individual organisms and entire ecosystems justify further exploration of the capabilities approach in application to design. For the discussion of these issues, see (Fulfer 2013; Bendik-Keymer 2020; Binder 2019; Carter 2014; Cripps 2010).

[7] For details of our earlier work on habitat-structures for powerful owls, see (Roudavski and Parker 2020).

enjoy, study, and support powerful owls. [8] This integration into an existing interspecies context makes the case study relevant as an illustration of complex interactions. These interactions include multiple bioregions, owl communities, and human groups including The Powerful Owl Project run by BirdLife Australia, biologists and ecologists specialising in powerful owls, local amateur collectives, urban municipalities, and management organisations.

This choice is also relevant as an instance where novel cultural imagination across species will be increasingly necessary. Design and management decisions that include powerful owls are important in response to ongoing habitat loss and degradation. This case-study is also useful because it highlights applications of justice theories to interspecies design that will be relevant in many other situations of environmental degradation and novel ecologies. Australian urbanisation and habitat destruction are illustrative of the global trends. Here, 10% of terrestrial mammals went extinct since the arrival of the Europeans and over 16% of birds are listed as threatened (Ward et al. 2021). Some 30% of threatened Australian species live in cities (Ives et al. 2016). The plight of owls who attempt to find ways to live alongside humans is similar to the challenges faced by many other species.

To establish possible goals for future interspecies design, we evaluate capabilities in human-dominated areas noting how powerful owls behaved (species norms) and fared (wellbeing) before colonisation and urbanisation. [9] This helps to provide benchmarks for possible restoration through design. [10] We use this approach because the restoration of capabilities may prevent future harm and compensate for past injustices. In three steps, we consider the:

1. ***Powerful owls in the past: evolved capabilities of powerful owls in pre-colonial Australian contexts*** (~300 years ago and earlier). We first outline the historical context of human and owl cultures and explain the environments that owls evolved to accept. We then use historical and scientific literature to list 12 capabilities of powerful owls. Instead of relying on predetermined sets, we recognise that different purposes may require different lists of capabilities. [11] We organise the list of powerful-owl capabilities

[8] Powerful owls are the largest of the Australian nocturnal birds. Endemic to eastern and south-eastern Australia, the conservation status of powerful owls is 'endangered' in the state of Victoria and 'vulnerable' in the states of New South Wales and Queensland. For more information on the powerful owl and the Powerful Owl Project, see (BirdLife Australia 2021).

[9] For background on this approach, see (Delon 2021).

[10] We consider this approach to be especially valuable in cities, where attempts to return the environment to previous states are unfeasible due to the expanse of existing infrastructure, extent of degradation, and possible lack of reference points for restoration. Further, aims to restore pristine wilderness (free of human influence) are not necessarily possible or desirable, especially where Indigenous communities held centuries-long land-management practices.

[11] For background, Nussbuam's theory of justice lists ten general capabilities that humans and sentient animals should be entitled to up a minimum threshold: life; bodily health; bodily integrity; senses, imagination and thought; emotion; practical reason; affiliation; other species; play; and control over one's environment (see Nussbaum 2007).

into three categories: health, autonomy, and affiliation.[12] These categories are sufficiently broad to allow comparisons with capabilities of other stakeholders, such as trees and possums, in future studies.

2. ***Powerful owls in the present: expression of capabilities by owls in Australian cities.*** To understand how colonisation and urbanisation restricted or enabled powerful-owl capabilities, we collect examples of owl behaviour from scientific literature, news articles, visual media, anecdotes, firsthand observations, and grey literature. Cross-checking these observations against the list of 12 capabilities (step 1), we identify the extent to which cities restrict or enable owl behaviours.

3. ***Powerful owls in the future: effects of current and aspirational design and management.*** To understand how interspecies design could impact the capabilities of powerful owls in cities, we extrapolate the trends established by current design and management actions. We then draw from recent design proposals to put forward possible interspecies approaches that could better support the goal of restoring capabilities.

4. ***Implications beyond powerful owls.*** To consider potential applications beyond the case of the powerful owl, we consider capabilities of other owls in other settings. We examine three categories of animals: captive, liminal, and wild.[13] Within these categories, we identify four representative human-owl cultures based on a taxonomy of human-animal relations that distinguishes between animals engaged in display and performance as well as meat, pets, experimental subjects, workers, and symbols (DeMello [2012] 2021).

We conclude with a discussion on the ethical challenges of designing for interspecies cultures and posit directions for further research based on this knowledge.

3 Results

The Results section presents our findings in four parts using tables and diagrams:

1. Section 3.1 collects an array of powerful-owl capabilities, offering a baseline for future design.

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[12] We acknowledge that this approach inevitably generalises and ask readers to treat the lists as an illustration rather than an exhaustive list of all possible capabilities. We do not claim that owls could utilize all capabilities or that owl wellbeing cannot improve beyond this state. Also note that our analysis also relies on more recent literature about owl behaviour in areas with less human disturbance because researchers only recently made the first assessments of the distribution, abundance, and conservation status of powerful owls (Department of Environment and Conservation 2006).

[13] For background on these categories, see (Donaldson and Kymlicka 2011).

2. Section 3.2 finds that cities diminish many capabilities of powerful owls but present opportunities for new cultural expressions, highlighting the need for design to target multiple aspects of powerful-owl wellbeing.

3. Section 3.3 develops visual mapping which indicates the possibilities for design to help restore powerful-owl capabilities in cities in a way that moves beyond current design and management strategies.

4. Section 3.4 presents the reusability of our approach in other cases, ascertaining the opportunities for context-specific and place-based applications to other taxa and human-owl cultures.

3.1 Powerful owls in the past: Cultural interactions as a baseline for design

This section describes past lifestyles and capabilities of powerful owls as a baseline for future design. Archaeological records confirm that human-owl cultures are old. Owls played an important role in the construction of landscapes, contributed to the senses of place and community, and even influenced the making of humanity (Hussain 2021). During the Late Pleistocene, owls increasingly shaped the material, cognitive, and social worlds of their human co-dwellers, prompting owl-directed human behaviours such as visual culture. *Ninox* owls, including powerful owls and the closely related Tasmanian spotted owl (*Ninox novaeseelandiae*), likely underwent an ancient radiation in Gondwanaland (Department of Environment and Conservation 2006). Powerful owls evolved to thrive in the old-growth forests and woodlands of south-eastern Australia (Figure 1) (Higgins 1990). They coexisted with the Indigenous Australian communities who thought that owls were important (Clarke 2016). Table 1 highlights how these conditions provided habitat and resources which enabled owls' capabilities. This offers habitat designers a benchmark for design that attempts to support a broad array of cultures and behaviours. [14]

[14] Refer to supplementary materials (A) for references and further details in support of Table 1.

Figure 1. Powerful-owl chicks in a hollow of a large-old tree. Photography: Nick Bradsworth.

Table 1. Baseline capabilities of powerful owls. Colours distinguish different capabilities to assist cross-referencing between tables and diagrams.

Capabilities	***Definition***	***Examples***
Health	*Live a normal length life, in good health and free from bodily intrusion or violence, with opportunities to develop a full range of senses.*	
Rest	*Choose favourable roosting sites.*	*Access perches with good shelter; camouflage and hide.*
Feed	*Practice typical hunting and foraging strategies and choose food.*	*Exhibit rare prey-holding behaviour for food storage or territorial display; maintain a mixed diet.*
Bathe	*Access water to drink, clean self, or regulate body temperature.*	*Bathe and drink in freshwater pools.*
Play	*Access sources of pleasure, enjoy recreational activities, or have adequate sensory stimulation.*	*Ferry bark-strips, snatch at foliage, swoop, hang upside-down on branches, and chase animals.*
Autonomy	*Make own decisions and have freedom of movement.*	
Move	*Choose when and where to fly.*	*Perform movements that support prey handling, foraging, and transit.*
Fledge	*Access adequate structures to land on when leaving nest and gain independence.*	*Access complex vegetative structure to land on when learning how to fly.*
Disperse	*Disperse into adequate territories and establish own home-range.*	*Disperse into areas without clustering; establish home-range in high-quality habitat.*
Defend	*Defend territory from threats.*	*Protect territory from intruders, including humans and conspecifics, via vocal displays or swooping.*
Affiliation	*Form rewarding relationships with others and have choice of attachment to others.*	
Socialise	*Develop and express the local dialect and have connections with conspecifics.*	*Practice different variations of the typical 'woo-hoo' call.*
Learn	*Develop local knowledge and expertise based on interactions with conspecifics or others.*	*Learn hunting strategies from parents and siblings or the routines of prey.*
Mate	*Find potential mates, court, and mate.*	*Bleat, duet, preen, gift food, and copulate.*
Nest	*Access potential nesting sites to incubate eggs and raise young.*	*Access large tree-hollows.*

3.2 Powerful owls in the present: Design for survival in novel ecologies

To identify opportunities for design, this section describes how powerful owls changed their behaviours in cities. Since European colonisation, exploitative land-management caused major ecosystem changes in south-eastern Australia. [15] Land-clearing destroyed over 50% of forest and woodland in New South Wales and 65% in Victoria (Department of Sustainability and Environment 1999). These changes restrict the lives of owls and leads to declines in owl populations (Higgins 1990). Present-day owl populations exist in dramatically modified landscapes and are increasingly common in cities (Cooke et al. 2018). Although researchers once thought that powerful owls are habitat specialists restricted to old-growth forests, powerful owls now inhabit Australia's densest cities including Sydney and Melbourne (McAllan and Larkins 2016; Cooke, Wallis, and White 2002). This suggests that owls can adapt to, tolerate, or even benefit from human-dominated landscapes (Figure 2). However, cities present owls with several challenges which threaten their wellbeing and prospects of long-term survival. [16] Urbanisation reduces the availability of critical habitat-structures that owls depend on, such as tree cover, structurally complex vegetation, and access to waterways (Isaac et al. 2014). This reduces the opportunities for owls to bathe, fledge, disperse, defend, socialise, learn, mate, and nest (Table 2). The restoration of these capabilities can serve as a target for design which moves beyond the usual goals of supporting bare-minimum biological necessities and towards other factors that are important for wellbeing and survival.

[15] Recent accounts have underestimated the magnitude of this ecological change, risking 'shifting baselines' for conserving owl habitat (see Bilney 2014).

[16] Refer to supplementary materials (B) for references and further details in support of Table 2.

Figure 2. Powerful owls expressing novel behaviours and inhabiting urban contexts. Top left: tearing a cooler bag. Top right: hanging off shorts (Credit: Choosypix). Right middle: using a birdbath (Credit: Andrew Gregory). Bottom left: nesting in an arboreal termite mound (Credit: Ofer Levy). Bottom right: roosting in an inner-urban/introduced tree (Credit: Lian Hingee).

Table 2. Present-day capabilities of powerful owls. Colours distinguish different capabilities to assist cross-referencing between tables and diagrams.

Capabilities	Definition	Examples
Health	*Owls are subject to several health risks in cities including car strikes, electrocution, attacks from introduced species, and secondary poisoning. Availability of healthcare in veterinary clinics or sanctuaries does not substantially alter this overarching trend.*	
Rest	*Limited sites for resting; possible susceptibility to disturbance including, noise, light, and infrastructure.*	*Use of sub-par roosts that do not allow effective thermoregulation; human-made roosting sites such as tennis-court fences, powerlines, and cars.*
Feed	*Less diversity but greater abundance of prey including possums.*	*Smaller home-ranges; novel food such as fish, koalas, and brush turkeys.*
Bathe	*Less availability of riparian areas for bathing.*	*Use of human-made bathing spots like bird ponds.*
Play	*Relatively unchanged opportunities to play, for example by swinging on branches.*	*Snatching of human-made objects of stimulation, such as clothing, cooler bags, and tea-towels.*
Autonomy	*Owls maintain autonomy in cities, but the destruction of habitats has reduced opportunities to fully exercise their capabilities. Urbanisation can affect animals' ability to live good lives by undermining freedoms and restricting options.*	
Move	*Continued freedom of movement but with more dangers when flying and less places to fly to.*	*Long-distance flight across areas of unsuitable habitat to connect to another habitat patch.*
Fledge	*Disrupted fledging due to the clearance of understory or tree-lopping practices.*	*Greater mortality of fledglings; adoption of orphan owls; human aid in rehabilitating/fostering fledglings.*
Disperse	*Less availability of suitable areas for offspring dispersal; risk of increased mortality, inbreeding and lower fecundity.*	*Young owls remain with their parents for longer.*
Defend	*Possibly more threats to defend territory from.*	*Techniques to defend territories from other owls and the mobbing of introduced birds.*
Affiliation	*Increased affiliation with humans in cities may positively or negatively affect owls' wellbeing. Some humans poach owls. Some urban owls habituate to human presence and enter places near humans.*	
Socialise	*Fewer opportunities to socialise with conspecifics due to sparse urban populations.*	*Interaction with humans and possible change in vocalizations between regions.*
Learn	*Greater need to adapt to cope with new threats.*	*Development of personality traits that help urban exploitation.*
Mate	*More human disturbance and fewer opportunities to find mates.*	*Possible breeding failure and infanticide due to human presence.*
Nest	*Less opportunity to reproduce because of the shortage and decline of old hollow-bearing trees.*	*Use of novel structures including introduced trees, human-made hollows, or arboreal termite nests.*

3.3 Powerful owls in the future: Designing for flourishing

This section considers whether current and possible future design and management strategies could meet the design targets established above. Most of the current design for owls relates to nesting. Provision of nesting structures is particularly important because the tree hollows suitable for nesting are rare and declining in cities. In one Australian city where powerful owls are present, the number of hollow-bearing trees in urban greenspace is likely to decline by 87% over 300 years under existing management practices. [17] Tree-planting alone is inadequate because it can take several hundred years until tree hollows become large enough for powerful owls (Gibbons and Lindenmayer 2002). In response, most of the current designs for powerful owls propose human-made tree hollows such as nest boxes or similar structures (Figure 3). While the human-cultural interest in supporting owls is encouraging, there is only one recorded occasion of a powerful owl using a human-made hollow, and even then, only one chick survived (McNabb and Greenwood 2011). Unsurprisingly, most advice for the management of future environments for owls urges managers not to rely solely on nest boxes. Instead, existing guidelines for planners, architects, and landscape architects focus on regeneration of vegetation, preservation of existing vegetation, and reduction of human impact on owls. [18] These mitigation efforts, combined with improvements to human-made hollows, may help to maintain powerful owl populations in the short term while revegetated environments mature. Still, the goal of reconfiguring cities in a way that allows owls to utilise their range of capabilities may necessitate cultural changes that depart from the *status quo* of urban management (Figure 4). This diagram shows how design goals could help to support expressions of powerful owl capabilities documented in Tables 1 and 2. The irregular edges of the lines indicate the approximate nature of such predictions. This visual mapping clearly indicates the need and possibility for more ambitious design to support powerful-owl flourishing in response to the destructive human-activities in recent pasts and projected futures of cities. [19]

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[17] Under a worst-case scenario, human activities such as clearing land for stock grazing and urban development may completely remove hollow-bearing trees from the urban landscape within 115 years. Even under a best-case scenario, the number of hollow-bearing trees will likely decline (Le Roux et al. 2014).

[18] For example, advice developed by owl-protection groups encourage: (1) regeneration of habitat by introducing indigenous trees that will eventually bear hollows along waterways and streets, providing pathways across roads using cables/poles, and planting complex vegetation on both public and private property; (2) preservation of habitat by protecting riparian areas, vegetation patches, and tree corridors, as well as retaining and pruning trees instead of removing; and (3) reduction of vegetation removal or direct harm to owls when constructing buildings (e.g., installing bird-sensitive windows that reduce collisions with glass), constructing tracks and paths, and introducing lighting near core habitat areas (Buchanan, Wortham, and Powerful Owl Coalition 2018).

[19] Refer to supplementary materials (C) for references in support of Figure 4.

Figure 3. Human-made hollows for powerful owls. Top left: carved hollow. Top right: carved log. Middle left: nest box. Middle right: repurposed wheelie-bin (Credit: Gio Fitzpatrick). Bottom left: hempcrete hollow. Bottom right: 3D printed wood hollow. Photography by the authors unless stated otherwise.

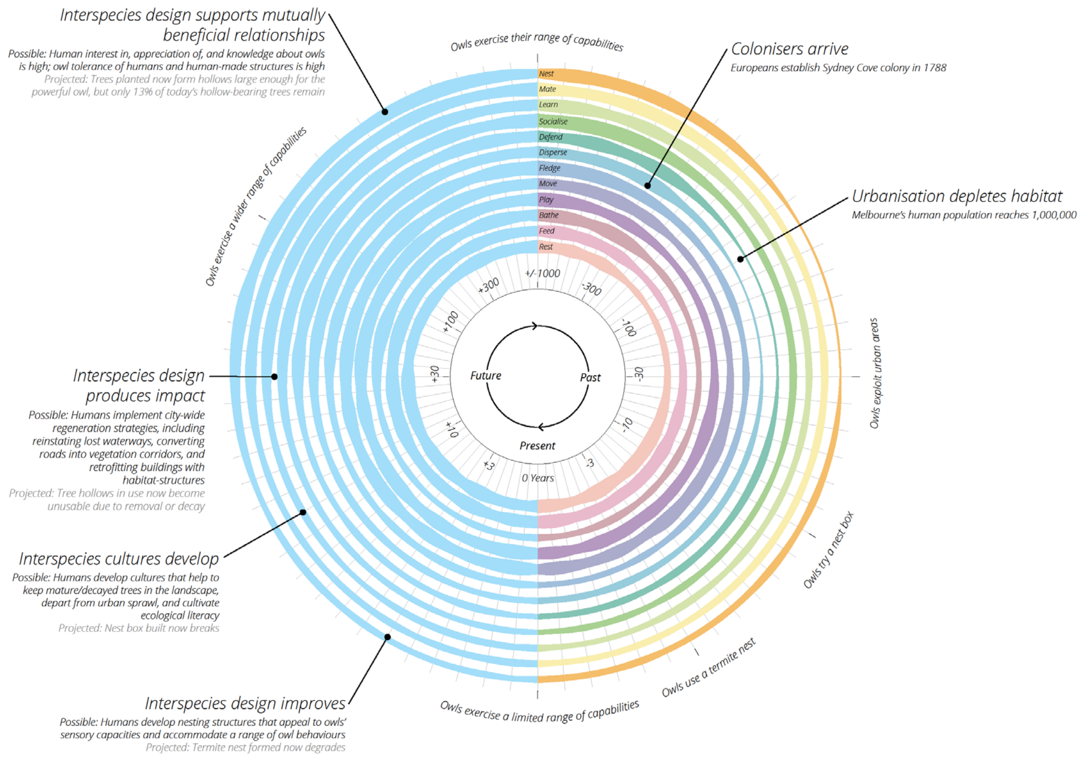

Figure 4. Design goals for capabilities. Right half: the impact of past events on powerful-owl capabilities (multi-coloured). Left half: projected situations under current design and management (grey text) and possible impact of design on powerful-owl capabilities in the future (blue). Colours distinguish different capabilities to assist cross-referencing between tables and diagrams. Line thicknesses indicate the likelihood of powerful owls expressing their capabilities, where thick = likely, medium = possible, thin = unlikely.

3.4 Beyond powerful owls: Capabilities in other taxa

While our case-study focuses on urban-dwelling powerful owls in south-eastern Australia, the capabilities approach has broad relevance to other situations. Table 3 presents these implications with examples of human-owl cultures at different sites and outlines the possible impacts on owl capabilities. Figure 5 takes the scenarios from Table 3 and illustrates how these human attitudes can affect the likelihood of owls utilising their capabilities. The irregular edges of the circles indicate the approximate nature of such predictions. Awareness of these interspecies relationships can inform the composition of design teams and help to establish more equitable objectives. The form of interspecies design will vary depending on whether the species are captive, liminal, or wild. For instance, owls raised in captivity will have more tolerance towards humans in comparison to those captured in the wild (Potts 2016). In the case of powerful owls, captive birds may live severely restricted lives and develop behaviours that are radically different to those typical in the wild. Wild powerful owls, when hospitalised or in aviaries, are often unsettled, stressed, aggressive towards handlers, and difficult to keep (Park 2003). Wild or liminal powerful owls also exhibit considerable behavioural differences in different regions. [20] This behavioural plasticity highlights the need for interspecies design that is context-specific and place-based.

[20] For example, urban owls demonstrate more tolerance of humans than rural conspecifics (refer to Table 2). For evidence of different behaviours across regions of Australia, see (Higgins 1990).

Table 3. Human-owl cultures globally and their potential impact on owl capabilities.

Relationship	Examples	Possible Impact on Capabilities
Captive	*Captive refers to animals that live among, depend on, or are confined by humans. Captivity provides some health benefits but risks diminishing owls' ability to exercise autonomy or maintain affiliation.*	
Experiment	*Humans use owls as medical subjects, for example neuroscientists gain insights into human brain function by analysing how barn owls learn.*	*Laboratory conditions do not allow owls to express their capabilities but support improvements to human health.*
Entertainment	*Humans keep owls for entertainment purposes, such as in zoo displays, acting, or in cafes.*	*Human aid means owls live longer but suffer heavily managed conditions that diminish their ability to maintain sound mental health, move freely, or socialise.*
Companion	*Humans keep owls as pets for conservation or affiliation purposes; popular films increase pet-keeping, illegal trade, and abandonment of pets.*	*Enclosures restrict owls' choice of attachment to others and freedom of movement, affecting their ability to develop local calls or hunting strategies.*
Patient	*Humans keep injured or ill owls as patients in medical clinics or sanctuaries; pre-release conditioning teaches birds how to survive in the wild again.*	*Human aid improves owl health but restricts autonomy in the short term.*
Liminal	*Liminal refers to animals that live in human settlements but do not necessarily affiliate with or depend on humans. Compared to captive owls, liminal birds have greater autonomy and opportunities for affiliation.*	
Labour	*Humans (falconers) train owls as hunting partners to acquire food – a practice existing for several thousands of years.*	*Enclosures reduce autonomy but typical hunting techniques resume. Owls regain autonomy upon release.*
Urban Visitor	*Owls adjust their behaviours to exploit urban environments, for example, by learning to make shelters or nesting sites instead of relying on existing structures.*	*Owls encounter urban threats that significantly reduce their opportunity to live full, healthy lives.*
Synanthrope	*Owls range freely, live closely alongside humans, and benefit from human activities; increased populations lead to humans viewing owls as pests.*	*More frequent encounters create mutually beneficial affiliation between humans, owls, and other animals but with additional risk of conflict.*
Mutualist	*Humans and owls establish mutually beneficial relationships; for example, humans provide nesting sites while owls keep rodents away from crops.*	*Owls maintain freedom of movement, choice of food and habitat, and opportunities to reproduce; human health and affiliation also improves.*
Wild	*Wild refers to animals that live apart from humans or have little to do with humans. Owls can express their full range of capabilities in the wild. However, human-cultural behaviours can still affect wild owls.*	
Omen	*Humans use owls as omens. Some humans think that owls are noble, beneficial, wise and benign beings; others view owls with superstition or pessimism.*	*Omens impact owls differently because they range from association with good luck and wisdom to bad luck, terror, evil, death, and sickness.*
Resource	*Humans treat owls as resources, hunting owls for food, making arrows, trading, magic medicine, or fun during hunting trips.*	*Hunting takes away owls' ability to live an autonomous and full-length life.*
Recluse	*Owls live rurally and separate from humans. Yet, conflicts still emerge, for example, in arguments between conservationists and loggers.*	*Conflict creates challenges but owls still exercise the range of their species-specific behaviours.*
Human Thought	*Owls exist only in human thought or representations including photos, documentaries, films, fairy tales, picture books, songs, commercials, or soft toys.*	*Extinction means owls no longer exercise any capabilities. Detachment contributes to an 'extinction of experience' in humans, harming health and affiliation.*

Figure 5. Illustration of the potential impacts of human-owl cultures on owl capabilities based on the examples in Table 3. Colours distinguish different capabilities to assist cross-referencing between tables and diagrams. Circle sizes indicate the likelihood of owls expressing their capabilities, where large = likely, medium = possible, small = unlikely. Rows: representative human-owl relationships. Columns: capabilities of owls.

4 Discussion

4.1 Case-study findings and limitations: Extending the capabilities approach

The objective of this article is to establish goals and evaluative practices for interspecies design. Our results demonstrate that the capabilities approach can support this objective by proposing and testing future-oriented design possibilities with respect to interspecies cultures. Our case-study focused on owls and points to the need for alternative design approaches that imagine what future interspecies design and culture can entail. These approaches should aim to incorporate more-than-human cultural interactions into design thinking (Section 3.1), provide targets for design that recognise rich and diverse lives of nonhuman species (Section 3.2), and encourage more ambitious design aspirations beyond business-as-usual (Section 3.3).

As an initial step towards developing an ethically justifiable and practically plausible theoretical framework for interspecies design, our examples exclude significant aspects that will require further research. In this paragraph, we list some of the limitations of the work presented here and the planned further research.

1. This article generalises capabilities for all powerful owls without detailed considerations of their local cultures or individualities. Future research ought to map and compare the capabilities and interactions of owls within interspecies communities across distinct bioregions and novel ecologies.

2. We focus on the interactions of powerful owls and humans, largely excluding other stakeholders. Future work should include relations with different human groups, from enthusiasts to scientists and park managers; prey such as possums and parrots; cohabitants and competitors such birds that also use hollows or attack owls because they see them as a threat. Beyond birds, plants, parasitic microorganisms, and other forms of life are also important as members of multispecies communities. Engagement with Indigenous peoples, cultures, and land-management practices can also be informative and is ethically necessary for future design but remained beyond the scope of this article.

3. Very brief engagement with extended timescales is another limitation. More thorough exploration of past and possible circumstances at different timescales, from evolutionary to phenological and circadian, can further inform design decisions. Our approach to deriving and documenting capabilities via tables and diagrams serves as a useful and reusable base to extend these investigations (Section 3.4). As we discuss below, such investigations reveal conflicts, practical and ethical challenges, and opportunities for design.

4.2 The ethical challenges of interspecies design: Directions for future research

Ethical issues of interspecies design warrant further conceptual and theoretical consideration. Here, we discuss the potential challenges of deciding when and why to intervene in the lives of others, who is entitled to design, what form the design takes, and how design changes nonhuman lives.

Why, or under what circumstances, should designers intervene? Should interventions wait until a species is on the brink of extinction or aim to supplement existing populations? One argument is that humans have a responsibility to assist the animals they make dependent or influence through habitat destruction (Palmer 2010). Sceptics will call out the apparent irony of installing human-made habitats in direct response to human-made habitat loss. Do financial provisions via 'nature offsets' make habitat-designers complicit in destructive practices like housing developments? [21]

[21] For further discussion on the ethics of offsets, see (Ives and Bekessy 2015).

Most will likely feel ambivalent when creating habitat structures that intend to offset past or future habitat destruction. Yet, there is a need to imagine culturally and ecologically sustainable futures that challenge the dominant, exploitative economic systems (Fry 2009). Even when designers might prefer systemic political and economic change, immediate interventions such as nest boxes can serve as an achievable measure that may help to avoid the extinction of certain species. However, such actions could result in the emergence of nest-box-loving individuals who might speciate from their natural-hollow conspecifics, with undesirable results.

Some will argue that humans should stop interfering with others' lives, stressing that human-made habitats are band-aid solutions or last-resort measures. This logic has merit but understates the value of human-made habitats including bird houses and bee hotels as culturally significant artefacts that can enhance human knowledge about and emotional connections with other species. Further, arguments which presume the binary separation of humans and nature are problematic. These separations break down under pervasive human impacts in the Anthropocene or when exposed to the non-dualist worldviews and practices of Indigenous societies (Head 2016). Cities or other human-altered landscapes provide critical habitat for many animals (Soanes and Lentini 2019). This reality reiterates the need for design that encourages mutually beneficial cultures between human and nonhuman cohabitants in cities.

Who is entitled to future design? Visions of more just futures require considerations of practices humans consider unjust, including the sufferers of this injustice and ways to eliminate or remedy harms (Biermann and Kalfagianni 2020). Contentions occur when simultaneously existing needs are not compatible. Examples include the interests of current and future generations, preferences of individuals and collectives, or misalignments between intrinsic and instrumental values (Hickey and Robeyns 2020). The provision of habitat for target-species presents one such challenge. For example, human support for powerful owls will impact other species such as possums. Some conservationists target charismatic animals, often attempting to help wider ecosystems via 'umbrella species' (Lorimer 2007). Research on speciesism contemplates cultural drivers that underpin human partiality for some species over others (Caviola, Everett, and Faber 2018). In the context of interspecies design, discourse on the ethics of selecting target species is less common but related frameworks do exist (Apfelbeck et al. 2019). This work recommends focusing on species based on the potential conflict with humans, their observability to humans, and what benefits they might create for human societies. We suggest that there are opportunities to consider nonhuman as well as human capabilities when making such decisions. While conflicts between capabilities of different stakeholders will eventuate, participatory deliberation that includes local knowledge can guide negotiation (Schlosberg 2012). The challenge for designers is to imagine the form and operation of these interspecies collectives (Westerlaken 2020). Recent design theories that attempt to work towards more just futures present opportunities to lead these efforts. [22]

What interspecies design is and does, including processes of making and propagation, may create unanticipated problems of sustainability. Designed products that serve to accumulate wealth or secure ongoing funding can drive consumerism and waste. Designers rarely take responsibility for the end-lives of what they design or the waste that occurs when new replacement products render existing ones unwanted (Tonkinwise 2019). In the case of powerful owls, this could become an issue if a human-made hollow design becomes popular and leads to bulk-replacing of existing nest boxes with new ones. This links to issues of ideational destruction, whereby designers undermine the value of existing designs to justify their replacement for something better (Tonkinwise 2019). Well-meaning efforts to supply habitat-structures can come with questionable claims of innovation. 'Powerful owl nest boxes' are available for purchase online, despite having no recorded success of attracting powerful owls. Such practices can mislead purchasers and lead to widespread installation of habitats that favour already abundant species. These issues highlight the need for critical reflection that considers possible consequences of interspecies design.

How humans intervene with the lives of others is matter of ethical concern. An important interspecies design issue pertains to augmentation and the inducement of physiological changes. Beyond supporting or restoring the critical needs of a species, design can enhance certain habitat functions. Should designers strive to provide maximal comfort, for instance through air-conditioning devices, or aim to mimic the bare-minimum affordances of known habitats which vary widely in structure, quality, and availability? On one hand, human-made structures can and do enhance the quality of life for some animals. This can lead to physiological changes, for instance, in the clutch sizes of bird eggs in nest boxes compared to those in tree hollows (Møller et al. 2014). On the other hand, human-made habitats can lead to dependence without guarantees of support. Human-made habitats, such as nest boxes, can create ecological traps that attract habitation but result in lower chances of survival (Demeyrier et al. 2016; Klein et al. 2007). In the design of human habitats, there are many guidelines and regulations that aim to prevent such damages and ensure the health and safety of occupants. Interspecies design would benefit from the establishment of similar regulatory frameworks. Conversely, regulations of human dwelling should demand the provision of habitat for other lifeforms. In either case, it will be important to ensure long-term accountability at temporal scales relevant to all stakeholders beyond typical project durations or human lifespans.

Going further, how might owls and other nonhuman stakeholders have a greater say in future decision-making? Knowing worldviews of others, human and nonhuman, is difficult (Nimmo 2012). However, nonhuman behaviour can serve as a form of voice (Meijer 2016). For example, owls communicate that they feel threatened by hooting, swooping, or balling up one

[22] Refer to transition design, critical design, speculative design, more-than-human architecture, and undesign (Coombs, Sade, and McNamara 2019).

foot and knocking it on a perch (McNabb 1996; Friends of Canadian Corridor 2020). The practice of including nonhumans as participants in decision-making processes is challenging, notably because humans inevitably mediate such voices (Heikkinen et al. 2019). A further challenge for design will be to learn about nonhuman preferences without being obtrusive, using captive animals for testing, or testing potentially dangerous designs in the field. Here, explorations of future possibilities via the capabilities approach can be especially useful.

Where design intervenes should inform decision-making processes. Interspecies design must respect the existing cultures and consider the implications their interventions may have for the local populations. To illustrate, re-introduction of wolves into an area they once inhabited caused the local elk to become more watchful, anxious, and fearful (Lorimer, Hodgetts, and Barua 2019). Similarly, as apex predators with multiple potential prey, encouraging powerful owls into cities could profoundly impact other local species. Both humans and owls may also alter their habits. Some owls will need to learn to live near humans and recognise human-made structures as possible habitats. Some humans will need to learn to tolerate or even appreciate owls and the environments that sustain these large birds. These values may clash with other human desires that include owning large dwellings, driving cars, or holding superstitious beliefs which shun owls. Therefore, future design must present compelling proposals with demonstrable benefits (Tonkinwise 2019). For instance, designers might emphasise the joy one experiences when witnessing an owl, or the ecosystem benefits an owl provides. Future design ought to engage with local communities in attempts to understand multiple worldviews, with awareness that supporting some cultures can and will diminish others.

5 Conclusions

This article introduces the need to cultivate interspecies cultures in response to human activities that harm nonhuman lifeforms and their communities. We propose that interspecies design can help to tackle this problem. Understood as a process of designing ***for*** and ***with*** multiple species, our framework for interspecies design incorporates human and nonhuman cultural knowledge. Such knowledge presents novel opportunities for design and fosters beneficial relationships between humans and nonhumans. However, interspecies design also presents ethical challenges. Engaging with these challenges, we investigate more-than-human conceptions of justice through the capabilities approach. Our project tests the capabilities approach in application to an ongoing project that aims to help powerful owls thrive in cities. By comparing past baselines with present-day behaviours, we demonstrate that cities restrict many aspects of owl lives. We also consider how possible human-owl cultures might support or hinder capabilities of urban inhabitants. Our analysis reiterates the significance of human cultures for the wellbeing of nonhuman lives. Significantly, we demonstrate that the capabilities approach can support nonhuman interests within the design process, establish more equitable design goals, and set clearer criteria for design ideas. Such findings have important implications for architects, urban planners, developers, local government, academics, educators, and conservation organisations who share the goal of supporting multispecies cohabitation in cities.

6 *Supplementary materials*

For published article and supplementary materials, see:
https://doi.org/10.14220/trns.2022.1.1.183

7 *Author contributions*

Dan Parker conducted the research, developed the argument for the manuscript, reviewed literature, wrote the drafts, and produced visual materials. Kylie Soanes provided ecological guidance and contributed to the development of the manuscript. Stanislav Roudavski conceived and developed the overarching ideas, directed the research, and contributed to all stages of manuscript production. All authors contributed critically to the writing and revision of the manuscript and gave the final approval for publication. The authors have no conflicts of interest to declare.

8 *Acknowledgements*

We respectfully acknowledge the Wurundjeri people who are the Traditional Custodians of the Land on which this research took place. The project was supported by research funding from the Australian Research Council Discovery Project DP170104010, Future Cities Grant (Melbourne Sustainable Society Institute), and William Stone Trust Fund (University of Melbourne). We thank Therésa Jones and Bronwyn Isaac for contributions to this research and their feedback on the drafts of the article.

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Chapter 3. Wings Over Concrete: Exploring Human-Owl Cohabitation in Urban Landscapes

Dan Parker, Kylie Soanes, and Stanislav Roudavski

Abstract

1. *Urban environments increasingly encroach on the habitats of native wildlife, necessitating a re-evaluation of urban planning and design to accommodate the needs of nonhuman species. This study focuses on the cohabitation of humans and powerful owls (Ninox strenua) in southeastern Australia, highlighting the need for new approaches to managing urban biodiversity.*
2. *Employing in-context and semi-structured interviews with individuals deeply engaged with powerful owls, alongside observations of owl behaviours, this research explores the complex relationships between human activities, urban design, and owl populations. The approach aims to uncover the multifaceted nature of human-owl interactions and the potential for mutually beneficial cohabitation.*
3. *The study reveals accounts of powerful owls exhibiting a range of complex behaviours, including mourning, teaching, and self-expression, underscoring their emotional depth and intelligence. These findings challenge views of animals as mere instinct-driven beings and highlight the intricacies of their social lives within urban contexts.*
4. *Human actions, including habitat destruction, significantly impact owl populations. However, our research identifies potential pathways for fostering positive human-owl interactions through urban design that prioritizes the needs of nonhuman inhabitants.*
5. *The synthesis of our findings offers crucial insights for urban planning and policy. It underscores the importance of creating inclusive urban environments that acknowledge the rights and needs of all inhabitants, promoting a shift towards more biodiverse and equitable urban ecosystems.*

***Policy implications**: This research calls for the integration of wildlife conservation considerations into urban planning policies, advocating for the design of cities that not only accommodate human residents but also support the cohabitation of diverse species. By recognising the complex behaviours and needs of powerful owls as indicative of broader wildlife challenges in cities, policymakers can develop strategies that ensure urban environments contribute to the conservation of native species and the fostering of rich, multispecies cultures.*

1 Introduction: Towards multispecies cohabitation

Living well with different species is key to creating vibrant, biodiverse, and equitable cities. However, the lack of understanding of nonhuman perspectives and cultures means that human actions often fail to support the full potential of interspecies societies.

The key objective of this article is to address knowledge gaps about the co-existence of humans and powerful owls (*Ninox strenua*) in urban environments. Previously thought to be old-growth forest specialists, these apex predators now also inhabit cities (Cooke et al. 2018). However, urban environments pose numerous challenges, including many forms of disturbance and fewer nesting sites (Isaac et al. 2014). We aim to understand the lives of owls, identify human actions that negatively affect owls, and explore mutually beneficial interactions. By collating stories from communities where humans and owls live in proximity, this article outlines steps toward convivial multispecies cohabitation, advancing research on interspecies collaboration in design and conservation (Parker et al. 2022; Parker, Soanes, and Roudavski 2022).

Our hypothesis is that design and management can benefit from a better understanding of current and possible interspecies cultures. To test this proposition, we structure the narrative in three components of multispecies cohabitation that consider: 1) nonhuman cultures including sensory worlds, decision-making, and communication of owls; 2) human cultures including the actions that harm owls; and 3) interspecies cultures that can provide beneficial templates for design and management.

1.1 Nonhuman perspectives

What behaviours illustrate the rich lives of owls?

It is important to understand the perspectives of other organisms in the midst of unfolding ecological crises and human-wildlife conflicts. Research across fields like animal geography (Wolch 1996), anthropology (Schroer 2021), conservation biology (Dyck 2012), ethology (Greggor et al. 2014), cognition (Lee and Thornton 2021), and biosemiotics (Farina 2021) aims to foster equitable interspecies relationships by recognising cultures, *umwelten*, and sensory worlds of different living beings (Edelblutte, Krithivasan, and Hayek 2022). Despite scepticism about comprehending nonhuman experiences (Nagel 1974), recent studies offer insights into their complex lives (Yong 2022), advocating for a shift from seeing animals as generic types with automated responses to recognising their agency and individuality (Nussbaum 2023).

Recent studies on owl capabilities exemplify such changes in perspective (Ackerman 2023). However, there remain many unknowns about the perceptual worlds, decision-making, learning, and communication of these birds that are cryptic, nocturnal, elusive, and difficult to study. Despite this, humans already know enough to better support owls and can learn more. Numerous anecdotes about the lives of powerful owls tend to appear online or in personal communications. Such evidence can offer insights into realities not captured in scientific literature and drive future research.

1.2 Human actions

What human actions negatively affect owl lives?

Powerful owls face significant challenges due to human actions such as urbanisation, deforestation, and land clearing for agriculture (Buchanan, Wortham, and Powerful Owl Coalition 2018). These activities encroach on owl habitats, reducing available nesting and foraging areas and affecting food resources. Sharing cities with powerful owls is now unavoidable and human impact on owls can be hard to notice. For example, exposure to toxic substances can lead to secondary poisoning when owls consume contaminated prey (Cooke et al. 2022). Human activities, such as land fragmentation, have profound effects on other wildlife too, often leading to detrimental consequences for various species (Narayan and Rana 2023). Noise, light, presence of humans, collisions with vehicles and windows, and attacks by dogs and cats are among the risks to urban animals that result in injuries and deaths (Taylor-Brown et al. 2019).

In many cases, changes in human cultural preferences could lead to significant positive and negative impacts on nonhuman populations. Identifying and promoting human behaviours that are more conducive to cohabitation is important. Improvements to current urban development practices are readily attainable, but substantial progress depends on the foregrounding of nonhuman stakeholders.

1.3 Interspecies cultures

What interactions foster mutually beneficial co-existence between humans and owls?

We frame the positive interactions between humans and owls as a form of culture, following the emerging discourse on interspecies cultures in environmental studies (Heise 2020) and in application to multispecies cohabitation (Roudavski 2020). Such interspecies cultures occur when diverse species coexist and share information via social learning (Brakes et al. 2021) as occurs, for example, in cooperative foraging between humans and honeyguide birds (Cram et al. 2022). The cultivation of mutually advantageous interspecies cultures can counteract intentional or inadvertent harms that cause individual suffering and negatively impact multispecies communities. Human activities can lead to the alteration, extinction, and creation of animal cultures (Gruber 2023). Interspecies interactions are flexible and can evolve swiftly (Thompson 1999) as has occurred in innovative bin opening behaviour displayed by cockatoos (Klump et al. 2021). Nonhuman animal culture can support conservation and alleviate human-wildlife conflicts (Greggor 2024) by creating opportunities for behavioural innovation in adaptation to novel ecosystems (Perry et al. 2021). This approach is essential for the wellbeing of both human and nonhuman species in shared habitats.

Many human cultures have paid persistent attention and ascribed various meanings to owls. Kinship and appreciation of owls as welcome neighbours become possible when humans acknowledge their similarity to other lifeforms (Safina 2023). Examples of successful cohabitation between humans and powerful owls exist (Zeleny 2023) but are rare and remain poorly documented. Devoted humans follow and assist owls but would benefit from more support to organise their knowledge, share their findings, and thus overcome threats to urban wildlife (Parsons 2023).

2 Methods: A stroll through the worlds of owls and humans

To explore existing and emerging human-owl cultures, we conducted in-context and semi-structured interviews with humans who have lived alongside powerful owls for many years.

2.1 In-context interviews

Our interviews align with walking methods in multispecies ethnography (Springgay and Truman 2018). Interviews can clarify knowledge, values, beliefs and decision-making of diverse stakeholders (Young et al. 2018). Semi-structured interviews, consisting of planned and opportunistic questions, allow participants to introduce unanticipated ideas and enable deeper discussion on emerging topics. Walking interviews or 'go-alongs' can assess sensory feedback, account for emotions, trigger memories, and encourage the sharing of experiential and embodied knowledge in the context of site observations (O'Neill and Roberts 2019). For example, forest walks can support learning about nonhuman lives (Mäkelä and Aktaş 2023) and produce richer understandings of place than conventional interviews (Evans and Jones 2011). Such immersive interviews can amplify the voices of knowledgeable and passionate humans who live next to or work closely with nonhuman stakeholders (Haldrup, Samson, and Laurien 2022).

2.2 Interview participation

The interviewees shared an interest in owls but had different backgrounds, including ecology, land management, nature writing, conservation practice, volunteering, citizen science, nature tourism, wildlife rescue, journalism, filmmaking, social media administration, blogging, and photography. All participants had extensive experience with owls ranging from 1 to more than 20 years, with more than 5 on average. Participants visited owls at least once per week, but usually several times and often daily during the breeding season. Some visits lasted up to 7 hours. We identified and invited possible participants through word of mouth, preliminary visits to owl habitats with local experts, searches of published materials, and suggestions from the interviewees. The recruitment concluded once no new relevant contacts were emerging.

We conducted ten interviews that lasted between 1 and 8 hours, combining to more than 30 hours in total. We met 19 humans, with one to eight participants per interview, and encountered a total of six owls. To preserve anonymity, but link responses to sites and situations, we label observations with 'interview group number' (IG1–10) and provide contextual information as needed.

When possible, we conducted interviews while walking through the habitats of owls such as the urban forest in Figure 1. The participants chose the locations of the walks in response to recruitment materials, our research articles, and preliminary email exchanges. Five interviews took place online due to COVID19 disruptions, but we visited most sites independently. In total, we visited 16 owl territories (one to five per interview) in Melbourne, Sydney, and

Brisbane, sampling the southern, central, and northern parts of their distribution. To capture a breadth of interactions, we explored sites with different attributes and levels of human activity. They included suburban bushland with remnant vegetation, backyards with nest boxes, golf courses, and urban parks close to transport infrastructure.

Figure 1. Snapshots from walking interviews in urban owl territories (left), including one of six owl sightings (right) (image by the authors).

2.3 Interview prompts

In order to address the three core gaps identified in the introduction and in keeping with emerging methods for the study of multispecies cohabitation (Delahaye 2023), the interviews covered the following:

1) **nonhuman perspectives,** prompting anecdotes of novel behaviour as observed in the use of human-made structures by owls, their ability to learn and play, and interactions with humans;

2) **human actions,** prompting accounts of local human communities' attitudes toward owls, obstacles to human-owl cohabitation, and views on current management; and

3) **interspecies cultures,** prompting examples of relationships and interactions illustrating successful cohabitation.

Ethical approval for this project (2021-22438-20716-2) was granted by the University of Melbourne Low or Negligible Risk Human Research Ethics Committee (LNR 1A).

3 Findings: Insights into existing and possible human-owl communities

Nine themes emerging from the interviews include aspects of 1) owl lives, as discussed in the sections on emotion, management, and communication; 2) impacts of human actions, as discussed in the sections on negligence, conflict, and knowledge; and 3) interspecies cultures underpinning human-owl cohabitation, as discussed in the sections on trust, understanding, and connection.

3.1 Lives of owls

3.1.1 Emotion

The interviewees discussed the emotional lives of owls, including their loyalty to mates and offspring. These emotions can motivate their selection of sites and influence breeding success. When owls lose their relatives, they show signs of mourning. In one example, a mother owl kept returning to the hollow where her chick died: "She seemed distressed and kept looking into the hollow as if searching for the chick" (IG3). In another example, when construction work killed the chicks, the parents continued to call for them for weeks and were reluctant to hunt or move from their tree: "They just stay in the same tree. They don't even hunt, they just sulk. And you can tell they're really upset. Like we knew straight away that the mother was just going 'where's the baby?'" (IG4). Others described similar distress when chicks died from drowning in a swimming pool (IG8) and after attacks by kookaburras (IG5) and cockatoos (IG6). These behaviours suggest that owls have a strong bond with their family members and even adopted chicks (IG3/8). Others have reported related stories, like how owls made grieving noises when fire ripped through a hollow they had been using for 10 years and killed their chick (Ackerman 2023). Several interviewees referred to reporting by Fleay (1968) (IG2/3/5/8), who mentions an owl dying of a broken heart (p.19) and mothers speaking in caressing tones to offspring (p.28).

A better understanding of such emotions can build solidarity through recognition of owls as sentient beings: "You begin to realise there's a lot more going on than you think. They are not simple automata, running around doing some automated machine-type process" (IG7). Such understandings can guide urban development in ways that minimise suffering. For instance, landscape elements such as recesses can minimise stress, fearful reactions, and conflict between humans and wildlife through vertical barriers that still maintain visual connection (Hwang and Jain 2021). In the case of owls, one interviewee mentioned a positive step in which a major urban development plans to create vegetation patches no more than 1km apart to support safe nesting, socialisation, and the dispersal of young (IG3). Negative emotions can influence how owls use such sites. In one example, a pair of owls changed hollows every year, moving further down a creek after successive failed breeding attempts (IG3). By recognising owls' attachments to each other and to sites, and integrating nonhuman stakeholders including owls into design processes (e.g., see Thomson et al. 2022), new developments could proceed in ways that improve wellbeing.

3.1.2 Management

Another set of complex owl-behaviours combine elements of hunting, land management, and teaching. Interviewees reported food management that resembles forms of farming in other nonhuman animals such as ants, termites, and beetles that cultivate fungi for food or engage in animal husbandry (Mueller et al. 2005). For example, owls often do not hunt in trees or backyards where they roost and nest (IG1/3/4). Instead, some preserve wildlife for their young to learn how to hunt: "They farm their prey. It's almost like it's their pantry" (IG4). These owls let brush turkeys (*Alectura lathami*) live nearby (IG8), allowing young owls to practise hunting by waiting on top of nest mounds constructed by turkeys until the chicks come out (IG4). Brush turkeys also benefit owls by removing undergrowth vegetation under tree canopies and making it easier for owls to fly (IG8) and catch their prey: "People don't realise how much the owls depend on brush turkeys; so, I don't chase the brush turkeys away because it would disturb the whole balance" (IG4). As these examples show, owls are not only adaptable to urban environments, but might also have strategies to manage prey in sustainable ways.

Owls can also develop innovative hunting techniques that adapt to unusual prey and make use of human-made structures such as powerlines and houses (IG2/5/7/9). Such techniques differ between individuals and groups. One pair, for example, used teamwork to catch possums: "You'll get one on this side and one on that side, and they'll just yell at the possum. And the possum freaks out and usually they'll chase it to the other owl" (IG4). Owl chicks apparently learn from their parents how to hunt (IG4) and parents teach their young to leave the nest site by withholding food (IG5) (Hollands 2008).

Design for owls should support such managerial behaviours to ensure that interventions align with their capabilities. For example, when designing human-made roosts or selecting vegetation species, understanding the preferences of owls is crucial. Owls have favourite parts of trees that they seem to show their partners (McNabb, Kavanagh, and Craig 2007). They like thick, horizontal branches where they can bond. Dense vegetation helps them escape from mobbing birds (IG1/3). They follow safe flight paths beneath cathedral-shaped tree canopies (IG8). Some use roosting spots near rock faces, which are cooler and more protected (IG3). This information on roost preferences can inform approaches to the management of large old trees and provide baselines for the design of perches that better match characteristics of tree branches in places where such trees cannot grow (Holland et al. 2023).

3.1.3 Communication

The expressive capabilities of owls (Figure 2) can support rich communication within and between species. For instance, some show curiosity by finding and persistently observing humans (IG3/4/8); wariness by shuffling, blinking, locking eyes with intruding humans, excreting to get rid of weight, suddenly leaving roosts, and swooping (IG3); and comfort when they look away, groom themselves (IG4), or fall asleep in the presence of humans (IG5/9). Owls also make calls to convey different meanings. These calls range from hoots to growls (IG6) and purring (IG4). Humans can learn to recognise these calls and understand what they mean. Some calls are for courtship (IG3), some are warnings, some are for communicating with other owls (IG4/10), and more are for expressing displeasure. For example, owls use sheep-like calls in various scenarios, such as when the mother owl communicates with the chicks or when the father owl tries to fend off crows (IG10). Courtship communication is particularly engrossing: “Before the female incubates, they do courtship display and there’s this chatter that they do, this little mumbling. They talk to each other. At that moment, they’re so engaged that all sorts of stuff goes on around them that they do not notice” (IG3).

The experience of our interviewees demonstrates that by observing and studying owls, humans can learn to interpret their personalities through signals such as facial expressions, body postures, vocalisations, and play patterns. Young owl play includes tug-of-war, feather pulling, and scaring from behind (IG4). These signals can reveal how owls adapt to their environment, interact with other species, express their needs, pursue their preferences, and enjoy their lives. For example, owls take turns throwing and catching objects on streetlights (IG3). The personalities of owls can vary depending on exposure to human contact. Some owls are shy (IG8), while others are curious (IG3/4/8), sanguine (IG3), and relaxed (IG10). Humans can notice these differences by paying attention to body language: “Dad’s very aloof… Mum’s always very alert, eyes wide, checking you out—we tend to keep away from her as much as possible. Dad will look at you and turn around like ‘whatever’. The chick is much more interested. He’ll be aware that you’re there. We’ve seen him hanging off vines upside down pulling things off. It looked like directed play in terms of the skills he might need to catch prey. The first time we saw him playing on the ground, he was playing with a leaf, just attacking a leaf and tearing it apart” (IG9). Interpretations of owls’ preferences and personalities have implications for the design of signs or other educational tools to encourage solidarity and guide human behaviour, including proximity, timing, and duration of contact.

Figure 2. Some of the many expressions of powerful owls, which humans can learn to interpret (images by Dr Nick Hamilton).

3.2 Impacts of human actions

3.2.1 Negligence

Governance failures have had significant detrimental effects on owl habitats. Our interviewees confirm the inadequacies of policies to support owls (Carter et al. 2024). Land management routinely removes roosts, for instance, because the trees are non-indigenous: "For the last 3 or 4 years, the owls spent the whole summer there and now they're gone. They used to roost in flame trees, maybe 30 or 50 years old. There were about six of them, and they were cut down this year because they weren't in the reserve, they were on the edge of someone's property, and they're not on the protected species list" (IG4). In another example: "The council said, 'had we known there were owls in that area, 72 houses would not have gone ahead'" (IG6). There are also cases of controlled burns and development projects in owl habitats due to inadequate or poorly timed ecological surveys. An example of this is the initial approval of a zipline in Queensland after a survey conducted outside the breeding season failed to detect the presence of owls (IG10). Light pollution is another feature of cities that affects powerful owls: “Now that the LED lights are next to the acacia, they don’t bring their chicks to crèche at all. And the male, where he used to roost and see the nest tree, they’ve put a LED light at the front of the house, and he’s now shifted” (IG3).

Despite existing legislation, land clearing for housing developments (IG2/7/8), illegal tree-felling (IG2/4), the removal of large old trees due to safety concerns (IG1/4/10), disruption of wildlife corridors (IG3/7), and pollution distributed to creeks through stormwater systems (IG2/4) contribute to the cumulative effects that lead to the increase in observed fatalities. In reduced habitats, juveniles land in unusual places, including a boat workshop, car, warehouse, semi-industrial area, shopping centre, and train (IG2/8). The gaps between vegetation patches create a risk of inbreeding if the populations cannot mix (IG3). This reality incites frustration: “The realisation that there’s a big conflict between the people who love the environment and the people who just want to build houses. That can be quite depressing. In particular, because people who want to build houses are so well funded. You feel like you’re up against it. It’s relentless. Every time you think you’ve dealt with one person who’s asking about a development proposal you get the next one and the next one and there just seems to be no end to it” (IG8).

There is a need for visions of future cities that gain public support for such proposals as establishing vegetation corridors guided by data on owl dispersal obtained through DNA analysis (IG2/8). Some interviewees suggested avenues in law enforcement, including acquiring properties from developers to establish habitats, using fines for illegal tree felling to back regeneration projects, and classifying areas of critical habitat as protected (IG2/4). Recognition of nonhuman lifeforms as political actors (Donaldson and Kymlicka 2011; Meijer 2019) or approaches that emphasise more-than-human commons (Büscher and Fletcher 2019; Herrmann-Pillath 2023) also hold promise to benefit owls, especially on private land where owners have no obligations to retain critical habitat structures.

3.2.2 Conflict

Public awareness and attitudes towards owls vary widely, often affecting conservation efforts. Many residents are indifferent or unaware of owls (IG3) and some illegally poison or cut down nest trees to enhance views (IG4) (Figure 3). Others are hostile towards owls, influenced by misunderstandings or confronting owl behaviours (IG4). For instance, some humans dislike owls’ hunting methods or their vocalisations, leading to a lack of support for their conservation: “Some people really hate them. They find them violent and horrible. One dude told me how he was watching a ringtail possum amble along the gutter and the owl came down and squeezed the possum. It popped the head off like a pez. The possum body was spraying blood out the neck hole. And then the owl dropped the possum. The dude was screaming. As the possum dropped down it sprayed his face with blood. And then the owl wanted its dinner and was bouncing off the house to get the possum and take it away. He was really traumatised by this affair. He was like ‘I never want those birds anywhere near me again’… And some people find them very noisy. One lady used to go ‘I just wish I could throw my boot at it' because it used to sit on her tv antenna and hoot" (IG3). There are also concerns that owls might attack pet cats or dogs (IG3/4/5/7/8). In reverse, owls become stressed by construction, playgrounds, mountain bikers (IG3/4/6), motorbikes (IG6), photographers (IG1/3/7/9), chainsaws (IG2/3/6), and dogs: "The male owl wouldn't care if ten people walked underneath, but if one of them had a dog then he would track it all the way along" (IG9). "He literally paced up and down the branch" (IG5). Councils are under pressure to allow residents to walk their dogs in protected areas, which is a danger to young owls on the ground and could result in abandonment of otherwise suitable habitat (IG4).

Most of the interviewees were reluctant to share the locations of owls due to the risks of increased visitation and disturbance. Some photographers accidentally or intentionally torment, provoke, or change the behaviour or position of owls to get a 'good' shot (IG1/2/5/7/9), for example, by wearing a welding mask to make owls swoop (IG3). Even well-meaning observers can accidentally flush owls from their roosts and direct the attention of other birds to owls, resulting in dangerous or even fatal mobbing (IG1/6/10). Such disturbances will worsen as cities expand and densify: "I think the parents try to move young owls out of this area as the city gets built up. The only ones I've heard of attacking are in urban green spaces where they are more confined and become more protective" (IG2). Therefore, it is necessary to design urban plans that respect the need for seclusion during breeding. For example, parks can include paths to guide humans away from core habitat areas (IG2), fledging platforms beside nest trees that support owls until surrounding vegetation matures (e.g., see City of Ryde 2021), and temporary barriers to reduce human intrusion during winter nesting before owls disperse (Olsen 2011) (IG3/5/8). Knowledge of individual owls and their tolerance to human activities can help determine tolerable levels of human proximity.

Figure 3. A nest tree for owls. Some residents illegally cut down or poison trees that obstruct views of the sea. A fledgling in the area of this tree landed on the ground and died from a dog attack (image by the authors).

3.2.3 Knowledge

The challenges of knowledge accumulation and sharing present several constraints on conservation. These include insufficient funding, tensions between enthusiasts, issues of volunteer engagement and retention, challenges in data collection and analysis, and inadequate coordination between conservation groups. As a result, some interviewees have not disseminated existing data on nest microclimates, films of owls, and notes on the interactions of owls and Indigenous peoples.

Knowledge of Indigenous Australians, whose ancestors have lived alongside owls for thousands of years and given owls different names, has suffered from European colonisation, but can still be valuable (IG3/7). The rapid landscape change since colonisation also means that the shapes of nests and roosts used to inform designs are likely suboptimal because owls have no choice but to use what remains. For example, owls often use old trees (Figure 4) that humans have not cut down for timber due to their twistiness, inaccessibility, or location in areas unsuitable for development (IG1/3/7).

The complexity, subtlety, and regional variability of owl behaviours make learning more challenging. Even the keenest of observers who spend hours watching owls cannot see everything owls do because eventually either the owl leaves or human leaves: “The more territories I see and the more different families I see, the more times I watch them, and more anecdotes I hear, the less sure I am about anything. There’s so much variation” (IG8). Under these conditions, anthropomorphic descriptions can be useful if they do not misinform (IG7). House hunting (IG5) and the tendency to stay with parents longer (IG2) provide two examples. Many interviewees gave familiar names to owls and described them as having similar emotions to humans: “The owls were watching the dog get closer and instinctively pulled their right foot up inside the plumage into a strike position. And they watched the dog with what I would consider amusement. The dog looked up, saw the owl, completely freaked, leaped, and ended up in the black mangrove mud. The owls just looked at the whole exercise as if it was humorous” (IG7).

Our interviews revealed debates over acceptable ways to interact with owls, the desire to be primary knowledge holders, and limitations in observation, data collection, and interpretation (IG3/5). These disagreements can result in a reluctance to collaborate, making conservation an even more challenging task. Volunteers often cease involvement due to dissatisfaction with the way projects are run, the lack of information sharing, and competition for credit or positions (IG1/7). The time and effort required to find owls also makes it difficult to sustain volunteer interest (IG10). Therefore, there is a need to upskill citizens and share knowledge more easily while making projects more exciting and persistent. It is also important to return information to the stakeholders' communities and demonstrate how knowledge leads to meaningful action. Additional knowledge about owls would inform the development in the interests of owls and other stakeholders. Community-led projects could drive the generation of this knowledge. As our interviews confirm, citizens can make high-quality observation. Some interviewees have documented events that refute existing claims about owl behaviours, such as that only males display prey during the day or that owls do not retrieve prey they were displaying and then dropped (IG9). With modest additional effort, field guides or public databases could support citizen scientists in compiling evidence of such novel behaviours (e.g., see Greggor 2024).

Figure 4. An old *angophora* tree used by owls. Such critical habitat structures may not necessarily be optimal for owls, but simply what remains, because the shape or location was too inconvenient for humans to harvest for timber (image by the authors).

3.3 Interspecies cultures underpinning human-owl cohabitation

3.3.1 Trust

Humans and owls can adjust their behaviours to be more mutually compatible. For instance, human actions can support interactions that respect owl preferences and build trust. Humans can aim to minimise disturbance by keeping distance (IG1/2/5/6/8/10), avoiding eye contact (IG3/10), and using less invasive forms of recording such as photography without flash or with red rather than white flash (IG1/2/6/7/10). Many interviewees are careful about sharing the locations of owls and aim to reduce the number of visitors, lengths of visits, and frequency of encounters. They reported how familiarity and trust can emerge through repeated encounters, predictable movements, and even talking to owls.

Similarly, owls can recognise humans and learn patterns of human behaviour. Owls respond differently to visitors they know (IG2/4/8), sometimes following humans as they walk, staying near houses, or roosting just metres away: "Some of the owls will greet us. They will trill when we arrive" (IG9). "The response of the bird is dramatically different when they know the person. It's not about the same clothes or saying the same thing every time you come in, it's definitely recognition" (IG3). "At night you can't see them, and they'll fly a couple of feet over your head, right up to the veranda" (IG1). "Often I'd go 'hello', 'hello'. 30 seconds later, sometimes I'd feel the swish of the wind. The owl would come down and fly past me. Then sometimes it would meet me down at the meeting spot or follow me. The first time it happened I was going, what do I do now? I thought, I just sit down. I'm going to enjoy the night and the sounds. So I sat there for about an hour and a half. And it was there, and called for food, it was watching things. And it would look over and put its head around so it's looking away from me, and it's having a snooze! How cool is this, like sitting on a rock with a pet powerful owl" (IG5). One interviewee installed a birdbath that provides respite in dry periods while his backyard supports a community of owls, parrots, turkeys, magpies, possums, and bandicoots, and beetles. "Most evenings my wife and I would have a fire, and when the owlets first came, they were fascinated about the fire, and were sitting above us, watching the fire. We'd be talking back to them. I noticed also that they'd be attracted to catching beetles near the fire. But I think they just enjoyed our company. In the mornings—we had a balcony out front—they would come and roost outside our bedroom window. I think it was just the whole environment that we created and the fact that they felt safe" (IG4). The cultivation of such relationships demonstrates the possibilities of mutually beneficial interspecies cultures where human and nonhuman residents learn to live together better and can serve as an aspiration for management.

3.3.2 Understanding

After spending some time looking for owls, interviewees begin to view places through the perspectives of owls and it becomes easier to understand their preferences, including favourite trees and branches: "Since I started following the powerful owl, I've noticed just how many creeks there are that I pass over in the car that I hadn't noticed before. I've been birding for 40 years, and I gained enough knowledge to start looking at the entire landscape differently" (IG9). Humans can learn where owls are and how they behave based on temperature and humidity, time of day and year, sounds and the behaviour of other animals, among other cues: "See how the owl is up the top of where the air is pushing up the rock face? When it starts to get hot like this, you'll only ever find them in this position" (IG3). Humans can further enhance their understanding of owls or other nonhuman beings. Some volunteers partner with dogs to locate owls (IG7), while ecologists use tracking devices to understand how and where owls move through urban settings (Carter et al. 2024). Audio and video are other useful ways that humans can use to tune into the lives of owls if there are concerns of disturbance, or where access is challenging due to terrain, distance, vegetation, or dangers such as ticks and snakes (IG1/2/6). Conservation activities would benefit from further research on the movements and fates of young owls that disperse from their natal territories (IG3/9).

A better understanding of owls would also aid the development of human-made nesting hollows and roosts. Examples of behaviours that require further research include the use of multiple nest entrances to allow each chick to perch and receive food independently (IG2/3), sharing trees with pardalotes, cockatoos, rosellas, butcher birds, possums and other species, the availability of nearby roosts from which the male can defend the hollow (IG1/3/4), and other nest characteristics including microbiomes and hygiene (IG3/4/10). “There’s probably a load of stuff owls perceive that we don’t. I think the reason nest boxes aren’t working is because they’re too dead. There is an amazing dynamic recycling environment that includes fungus, microbes, and beetles in a tree hollow that we don’t replicate in a nest box. We can’t replicate nesting sites until we understand how tree hollows work” (IG3). Further research into how owls perceive and learn to use human-made habitat structures is important because nest boxes intended for owls have not received much use (Buchanan, Wortham, and Powerful Owl Coalition 2018) even as owls increasingly use other urban features, including street signs, cables (IG3), letterboxes (IG2), and antennas (IG8). The use of cameras provides valuable opportunities to gather novel information on behaviours around nests (Parsons 2023).

3.3.3 Connection

How do humans become connected to owls and can existing connections become more common? Understanding motivations to coexist with owls can encourage engagement with nonhuman cohabitants, for instance, through education about personal benefits as well as benefits for owls. Across human cultures, willingness to endorse conservation policies depends on how much humans like a given species (Bruder et al. 2022). Therefore, familiarity and foregrounding likable characteristics can be important.

Our interviews highlighted several positive aspects of living alongside owls. Several interviewees enjoy long-term learning about owls and their ability to surprise (IG6/8/9). They describe the thrill and satisfaction of finding owls and nests (IG6/8/9). Some interviewees described awe of owls’ beauty, might (IG5/6/9), and elusiveness (IG1/4). Most of the interviewees reported benefits for their mental or physical health. For several interviewees, seeing owls is a positive social activity: “Having the community watching the nest has done quite a lot for people’s awareness of the fact that there are owls here and how important some of those trees are. It would be great if owls just became part of the norm, and you’d just point them out like tawny frogmouths ‘and there’s an owl’. Sometimes there would be ten or more people watching the owls and it was like a little community. You got to know people, you got to know their names” (IG9). Some interviewees became fascinated with owls after chance encounters (IG3/10), underscoring the importance of seeing more owls in cities. Furthermore, several interviewees noted preferences for larger houses with smaller backyards (IG2/4/10), which diminish corridors and disconnect residents from wildlife (Figure 5): “I’ve watched where I live which is right in the zone of ‘knock down these 1950s brick houses and replace them with the 1m-setback-black-roofed-grey-brutalist-structures’. The residents are never going to know urban wildlife” (IG7).

Out of affection for owls, interviewees speak on their behalf in council meetings, write to leaders, attend protests, and participate in community organisations (IG2/4). Humans can also work to stop development, obtain funding, or seek to increase the societal approval of conservation projects through education on roadkill, glass strikes, rodenticide poisoning, cats, dogs, and lighting (IG2/3/4/7). Actions can include rescuing owls, requesting or maintaining signs that guide public behaviour, and centring owls in books, songs, community rallies, and street art (Cameron and Bianchino 2017).

Figure 5. Contrast of older houses with more vegetation (left) and newer houses with less vegetation (right) in the greater Sydney area where owls are trying to persist (images from NearMap).

4 *Discussion: A synthesis of opportunities to benefit human-owl cohabitation*

Our investigation into interspecies cultures between humans and powerful owls (*Ninox strenua*) in southeastern Australia has highlighted a complex interplay of cohabitation that challenges conventional views on wildlife interactions and planning in urban environments. Through in-context and semi-structured interviews with humans who are closely involved in the lives of owls, we have gained a rich understanding of owl behaviours, the impact of human activities, and the evolving interspecies cultures that can both support and hinder co-existence.

Considering our motivations to create more equitable, convivial, and healthy multispecies cities, the findings of this study are significant. Typically, urban development and everyday practices pay little attention to nonhuman inhabitants, often leading to adverse impacts on wildlife (Narayan and Rana 2023; Taylor-Brown et al. 2019). Our research underscores the urgent need for a shift in the perception and management of interspecies relationships within urban environments, advocating for an inclusive approach that respects the needs and rights of all urban inhabitants, human and nonhuman alike. The reported behaviours of powerful owls, including mourning, teaching, and self-expression, shed light on their complex inner lives and social interactions. These observations contribute to research challenging the simplistic view of animals as instinct-driven beings, instead revealing their capacities for emotion, intelligence, and culture (Edelblutte, Krithivasan, and Hayek 2022). This insight not only enriches human comprehension of owl lives, but also calls for a thoughtful redesign of urban areas to support the diverse needs of nonhuman dwellers. Furthermore, the negative consequences of human actions on owls, such as habitat destruction and pollution, emphasise the need for conservation efforts that foster genuine cohabitation, recognising the fluid and dynamic nature of interspecies relationships. This entails a broad-based shift in behaviour and a societal recognition of opportunities for multispecies communities.

Our exploration of interspecies cultures offers a hopeful vision of urban living, characterised by mutual respect, understanding, and support. The instances of successful cohabitation that we have documented provide valuable insights for urban design, highlighting ways to enhance the welfare of all city residents. Positioned within the broader scholarly conversation on animal cultures (Brakes et al. 2021; Greggor 2024; Heise 2020) and the rights of nonhuman entities (Donaldson and Kymlicka 2011; Nussbaum 2023), our study expands the dialogue on multispecies approaches to design and conservation (Roudavski 2020; Wolch 1996). It provides further evidence of the potential to simultaneously benefit humans and wildlife in cities, complimenting efforts to include owls and other species as stakeholders in new urban developments (Thomson et al. 2022; Kirk et al. 2021). By outlining actionable steps to improve human-owl relations, we offer a guide for creating more equitable and biodiverse urban ecosystems. Based on these findings, we aggregate challenges, opportunities, and future research that can benefit human-owl cohabitation (Table 1). We outline future possibilities in three domains.

1. **Owl preferences and urban design:** Our study reveals undocumented owl behaviours that have significant implications for urban design. These behaviours, indicative of owls' emotional depth and complex social lives, demand a reconsideration of urban spaces to accommodate their needs. Design strategies that reflect owl food management practices and social behaviours, including the use of targeted landscaping and the creation of educational materials, can mitigate the negative impacts of city life on these birds.

2. **Human impacts and solutions:** We identify several human activities that adversely affect owls, indicating the necessity of integrating wildlife considerations into urban planning. The development of governance strategies that take into account nonhuman interests and the design of urban areas that reduce owl stress are critical. Additional support of community science initiatives can also improve human understanding of owls and inform less intrusive urban design.

3. **Interspecies cultures and aspirations:** Our findings underscore the potential for thriving multispecies communities based on respect and understanding. Encouraging such cultures requires urban environments that facilitate positive human-owl interactions. Designs that support owl habitats while accommodating human use of

urban spaces and cultural initiatives centred on owls can support the goal of convivial cohabitation.

By comprehensively addressing these aspects, we envision an urban future where actions are enriched by better understanding of nonhuman lives and capabilities, making cohabitation more feasible and desirable.

Table 1. Design objectives, possible actions, and open research questions.

	Themes	**Objectives**	**Actions**	**Research topics**
Owls	Emotion	Minimise suffering	Use the needs and capabilities of owls to plan urban spaces	Owl cognition, emotion, and behaviour in cities
	Management	Provide resources	Refer to owl behaviours to guide landscaping and planting	Responses of owls to place configurations and inhabitants
	Communication	Increase awareness	Inform humans through signage and other educational materials	Ways to enhance human interpretation of owl behaviours
Humans	Negligence	Improve governance	Protect, link, and create habitat zones	Research policies and laws to centre nonhuman stakeholders
	Conflict	Reduce disturbance	Design barriers and aids to support safe mutual use	Intervention based on individual and group characteristics
	Knowledge	Bolster information	Support citizens and encourage collaboration	Better documentation, data standards, and protocols
Interspecies	Trust	Encourage kinship	Cultivate landscapes that foster co-presence and sense of safety	Benefits and risks of proximity and interaction
	Understanding	Support learning	Design bio-informed nesting sites and other structures	Perception and usage of habitat structures
	Connection	Stimulate interest	Act on community-led initiatives that promote care and conservation	Technologies and methods for human-owl collaboration

5 Author contributions

Dan Parker, Kylie Soanes and Stanislav Roudavski conceived the ideas and methodology; Dan Parker collected and analysed the data; Dan Parker, Kylie Soanes and Stanislav Roudavski led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

6 Acknowledgments

We acknowledge the Wurundjeri, Gadigal, and Turrbal people as custodians of the lands where we conducted this research. We thank all participants for their generosity to us and, especially, to the owls.

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Chapter 4. A Framework for Computer-Aided Design and Manufacturing of Habitat Structures for Cavity-Dependent Animals

Dan Parker, Stanislav Roudavski, Therésa M. Jones, Nick Bradsworth, Bronwyn Isaac, Martin T. Lockett, and Kylie Soanes

Abstract

1. *The decline of critical habitat-structures, such as large old trees, is a global environmental challenge. The cavities that develop in these trees provide shelter and nesting sites for many species but can take centuries to mature. Artificial cavities, including nest boxes and carved logs, offer an increasingly important conservation response. However, current methods of designing, manufacturing, and deploying such habitats have constraints that limit innovation, feasibility, and effectiveness. In response, this article aims to provide new and broadly useable methods that can improve the design of habitat structures for cavity-dependent animals.*
2. *To address the shortcomings of existing methods, we develop an approach that uses computer-aided design techniques of generative and parametric modelling to produce structures that satisfy stakeholder needs, computer-aided manufacturing techniques of 3D printing and augmented-reality assembly to build functional prototypes, and computer-assisted techniques of laser scanning and data-driven design to support installation, monitoring, and iterative improvement of designs. We demonstrate this approach through a case-study project that designs and installs habitat structures for the powerful owl, Ninox strenua, a cavity-dependent and threatened bird.*
3. *Through comparison with existing methods, our pilot study shows that computer-aided design and manufacturing can provide novel and useful approaches to develop artificial habitat-structures. Computer-aided design finds geometries that approximate the complex characteristics of natural tree cavities and automatically produces new versions to suit diverse sites or species. Computer-aided manufacturing integrates materials that match the performance of naturally occurring habitat structures and facilitates the assembly of complex geometries by non-experts. Computer-assisted techniques produce precisely fitting and easy-to-install designs which support gradual improvement through ongoing prototyping and evaluation.*
4. *These capabilities highlight how advanced design techniques can improve aspects of artificial habitat-structures through geometric innovation, novel construction techniques, and iterative exploration. Significantly, computational approaches can result in designs that can perform well, are easy to construct and install, and are applicable in many situations. Our reusable workflow can aid in the tasks of practical conservation and support ecological research by effectively negotiating the needs of both humans and target species.*

1 Introduction

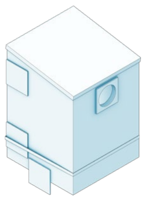
Habitat degradation and loss are among the greatest threats to life on Earth (Díaz et al. 2019). Human-induced landscape changes such as urbanisation and agriculture routinely remove or damage critical habitat structures, limiting species' ability to persist (Le Roux, Ikin, Lindenmayer, Blanchard, et al. 2014). Restoration efforts commonly focus on revegetation (Hale et al. 2019). However, this management practice can be insufficient if critical habitat elements cannot regenerate or mature rapidly enough to support animal populations, or if the landscape is heavily modified and lacks opportunities for natural regeneration (Le Roux, Ikin, Lindenmayer, Manning, et al. 2014). Human-made habitat structures that restore or improve habitat opportunities are increasingly important for the conservation of species. Commonly referred to as 'artificial habitats', examples include artificial roosts for bats (Mering and Chambers 2014), artificial rocks for reptiles (Croak et al. 2010), artificial reefs for fish (Baine 2001), and utility poles as artificial trees for birds (Hannan et al. 2019). While such habitats are increasingly common, evidence on the effectiveness of their design is varied (Gleeson and Gleeson 2012).

Provision of effective wildlife habitats is a pressing challenge faced by ecologists, conservation practitioners, land managers, and designers (Felson 2013). The rising use of artificial refuges exemplifies these challenges (Cowan et al. 2021). For example, artificial tree cavities have become necessary due to the global decline of large old trees and the natural cavities they provide (Le Roux, Ikin, Lindenmayer, Manning, et al. 2014). Tree cavities, also known as hollows, provide critical shelter and nesting opportunities for many species of birds, mammals, reptiles, and amphibians, yet can take hundreds of years to develop (Gibbons and Lindenmayer 2002). The installation of artificial cavities, such as nest boxes, can play a significant role in the conservation and management of habitats for cavity-dependent animals (Lambrechts et al. 2010). However, there are multiple aspects that restrict the effectiveness and feasibility of such structures. In Table 1, we list the benefits and limitations of three main approaches to the implementation of artificial cavities: (1) construction of nest boxes, (2) reuse of natural structures, and (3) carving of holes into existing structures. Using this comparison, we identify three areas where significant improvements are necessary and possible: design, manufacturing, and deployment. While there is limited knowledge on what design features species prefer, features such as entrance size and position, cavity proportions, and materials influence cavity uptake (for example, in arboreal marsupials, Rueegger, Goldingay, and Brookes 2013). Beyond use by target species, there are many criteria that determine the effectiveness of artificial cavities (Table 1). Our aim is to build off the successful aspects of existing designs and address the shortcomings.

Contemporary techniques of computer-aided design and manufacturing have strong potential to enhance the creation of habitat structures at diverse sites and scales. Computer-aided design techniques use software to generate and represent ideas through 3D models and 2D drawings (Dunn 2012); while computer-aided manufacturing uses digital technologies to automate the production and assembly of objects (Caneparo 2014; Dunn 2012). Tools for computer-aided manufacturing include laser cutting, computer-numerical-control (CNC) milling, 3D printing, and augmented-reality assembly. These computational approaches enable designers to conceive and build structures that are impractical with conventional methods. Benefits of computational-design innovation are evident in many domains, including automotive and aerospace industries, engineering, industrial design, and architecture. To date, the application of these techniques to ecological-habitat design predominantly occurs in marine habitats, such as seawalls made from 3D-printed moulds (Strain et al. 2018; Bishop et al. 2022) and laser-cut reefs based on 3D scanned corals (Vogler, Schneider, and Willmann 2019). The use of 3D printing to improve the longevity and thermal properties of nest boxes (Callan 2019) provides a partial example but such applications remain rare. Computational approaches present a novel opportunity to address the limitations in the design, manufacturing, and deployment of artificial cavities for wildlife habitat (Table 1).

We present a framework for using computer-aided design and manufacturing to improve the creation of habitat structures for cavity-dependent animals. We illustrate the real-world practicality of this process through a case study which designed, manufactured, and deployed cavities for a large owl species, the powerful owl, *Ninox strenua*. While focusing on powerful owls, the primary purpose of this article is to present a methodological framework for computationally designed cavities that can be useful for multiple species. Evaluation of the ecological, population-level outcomes for the owls will require several years of monitoring and is beyond the scope of this study. However, productive implementation of decision-making frameworks in conservation (Bolam et al. 2019) demonstrates that it is possible and necessary to assess decision quality independently from the success of the outcomes. Designers can make better decisions when they have distinct alternatives and evidenced methods for comparison. In the case of artificial cavities, better design decisions can make better designs more likely. Following this reasoning, we evaluate the proposed methods by comparing their benefits and limitations with existing alternative approaches against a broader range of criteria than typically considered (Table 1). This comparison demonstrates that computational tools can support systematic innovation and iterative development of designs that integrate multidisciplinary expertise.

Table 1. The benefits and limitations of existing ways to create artificial cavities. Images by the authors. Repurposed structure image developed with Alex Holland, Anton Maksimenko, and the Australian Synchrotron.

Method	Nest Boxes	Repurposed Structures	Carved Cavities
Typical structure			
Description	Addition of hollow boxes to existing structures such as trees or buildings	Salvaging and re-installation of habitat-structures with cavities such as fallen logs	Excavation of holes in existing structures such as trees or logs
Design			
Approximation of natural structure	Low: rectilinear boxes may not match the appearances or functions of natural cavities	High: can approximate the utility of natural cavities which are familiar to the target species	Moderate: may approximate natural cavities over time
Diversity of geometries	Low: rectilinear boxes do not match the diversity of natural cavities (Le Roux et al. 2016)	High: growth patterns of branches result in unique geometries	Moderate: use of tools, such as chainsaws, constrains the geometries
Capacity for modification	Low: difficult to revamp; typically modifications focus on entrance sizes, cavity dimensions, and materials (Lambrechts et al. 2010)	Low: little control over geometry and difficult to adjust	Low: limited by constraints of existing structures; little control over geometry
Manufacturing			
Availability of materials	High: prioritises conveniences of human construction, typically made from off-the-shelf and easily available materials	Low/Moderate: constrained by limited availabilities of found cavities	Moderate: dependent on the presence of large trees (Carey and Sanderson 1981)
Sustainability of materials	Variable: often poor but vary, including wooden planks or plywood, plastic, and woodcrete	High: recycles natural materials which are organic, non-toxic, renewable, and locally sourced	High: utilises existing trees and often does not require additional materials
Ease of construction	High: cheap and easy; guidelines for ‘do-it-yourself’ construction exist	Moderate: edits to structure may be necessary, such as drilling larger holes or adding bases and roofs	Low: often requires specialist labour and equipment
Deployment			
Ease of installation	Moderate: easy to hoist lightweight boxes but difficult to accurately position on complex tree geometry	Low: usually heavy, unwieldly, difficult to transport, hoist, and position	Low: limited by constraints of existing structures and requires specialists
Minimization of impact on installation sites	High/Moderate: some fixings such as nails damage trees	Moderate: can involve pruning of branches	Low: damages or even kills trees (Rueegger 2017)

Lifespan	Variable: range from less than four years (Lindenmayer et al. 2017) to 10 years (Lindenmayer et al. 2009) and longer (Goldingay, Thomas, and Shanty 2018)	Variable: dependent on age and weathering; long-term studies on attrition are needed (Griffiths et al. 2018)	Variable: often short, sometimes less than three years (Carey and Sanderson 1981; Terry, Goldingay, and van der Ree 2021)
Microclimate conditions	Variable: often poor (Maziarz, Broughton, and Wesołowski 2017); usually untested	High: well insulated (Griffiths et al. 2018)	High: similar to natural cavities (Griffiths et al. 2018) but can lack drainage (Terry, Goldingay, and van der Ree 2021; Carey and Sanderson 1981)
Use by target species	Variable: can support endangered species (e.g., Brazill-Boast, Pryke, and Griffith 2013) but can perform poorly (Lindenmayer et al. 2009; 2017) and attract non-target species (Stojanovic et al. 2020)	Moderate: can attract target species (e.g., mammals, Suckling and Goldstraw 1989)	Variable: can attract target species (Griffiths et al. 2020; Terry, Goldingay, and van der Ree 2021; Rueegger 2017) but sometimes unsuccessful (e.g., birds, Stojanovic et al. 2018)

2 A framework for computer-aided design and manufacturing of cavities

We developed an approach which draws on computer-aided design and manufacturing to improve the implementation of artificial cavities by addressing limitations in design, manufacturing, and deployment (identified in Table 1). To develop this approach (Figure 1), we first identified the aims and testable criteria for successful cavity design through stakeholder engagement. Collaboration between designers and conservation biologists, and the integration of knowledge from multiple stakeholders, is valuable to habitat-creation projects (Whitelaw, Hwang, and Le Roux 2021). Our stakeholder engagement involved workshops and consultations with ecologists, designers, local government, university-grounds staff, arborists, and engineers (see Table S1 in supplementary materials for details on the stakeholder consultation and the resulting design criteria). The feedback from these sessions helped to outline the needs of each stakeholder, including possible target and non-target species. We then selected computer-aided design and manufacturing techniques that had the capability to respond to these needs, while addressing the common problems of artificial cavities. Below, we outline the stages of our approach:

Design Phase

1) *Create geometry using generative design*: The first stage of our approach ‘finds’ geometric solutions that meet the design criteria set by stakeholders, using the process of ‘generative design’. Generative approaches exist in several fields including visual arts, music, design, architecture, and engineering. Consequently, “generative design” is a contested concept with a complex history and diverging definitions. Here, we follow a common understanding in architecture and design, and define generative

design as the use of algorithms to automate production, evaluation, and selection of design options (Caetano, Santos, and Leitao 2020). Rather than offering a single solution, these processes prioritise 'form finding' over 'form making' by exploring multiple possible solutions (see Agkathidis 2015 for illustrations). By contrast, approaches such as nest boxes predetermine their geometries (i.e., shapes) and only allow for small variations. Of relevance here is the capability of generative techniques to simulate processes of biological morphogenesis (Roudavski 2009) and match the geometries of natural habitat structures.

2) *Adjust geometry using parametric modelling*: Our approach then uses parametric modelling to alter the cavity design to suit case-specific circumstances, such as sites, habitat types, or species' requirements. In design, parametric modelling is an approach that expresses design elements (e.g., geometries and sizes), and the relationships between design elements (e.g., spacing and position), as adjustable parameters (for an overview, see Woodbury 2010). Architects, for example, utilise parametric techniques to make real-time adjustments to building designs (Patrick Schumacher 2016) and rationalise construction (Caneparo 2014). We adopt this approach to support efficient generation and modification of artificial-cavity designs to suit a broad variety of contexts.

Manufacturing Phase

3) *Make components using 3D printing*: This stage aims to manufacture cavities using materials that can suit potentially competing stakeholder needs. For example, cavity inhabitants require materials that are safe, non-toxic, durable, drainable and ventilatable, while human stakeholders may require materials that are affordable, efficient to produce, repeatable, weight-appropriate, low-waste, biodegradable, organic, locally available, and renewable. We propose 3D printing as an approach that meets these criteria and approximate the properties of natural habitats. 3D printing supports fast prototyping, mass customisation, minimises waste, and can repeatedly produce complex geometries (Ngo et al. 2018).

4) *Assemble components using augmented-reality templates*: This stage uses augmented-reality templates to assemble the cavity components with efficiency, ease, repeatability, and precision. Here, humans wear head-mounted displays that allow them to visualise digital guides atop physical objects to assist the assembly of complex designs and reduce the need for expert knowledge during construction (Jahn et al. 2019).

Deployment Phase

5) *Install prototypes using 3D scanning*: This stage harnesses laser-scanning techniques to overcome the difficulties of installing cavities on the complex structures and in difficult-to-access locations that many organisms often prefer. We demonstrate that light detection and ranging (LiDAR) (Beland et al. 2019) can help to identify suitable

locations within the tree canopies. LiDAR can create detailed, three-dimensional descriptions of potential installation locations, providing precise guides for the subsequent design of cavities that fit the host sites and result in safer, simpler and installation.

6) *Manage prototypes using data-driven design:* The final stage supports continual assessment and redesign of cavities based on performance criteria such as thermal stability, strength, ventilation, and the behavioural responses by target species. Importantly, this stage considers criteria established by the stakeholders, allows improvements in decision quality, and encourages a holistic assessment of performance. Prototyping facilitates improvement through the production of multiple versions in response to ongoing data collection, and allows for the comparison of multiple designs (for an overview, see Burry and Burry 2016).

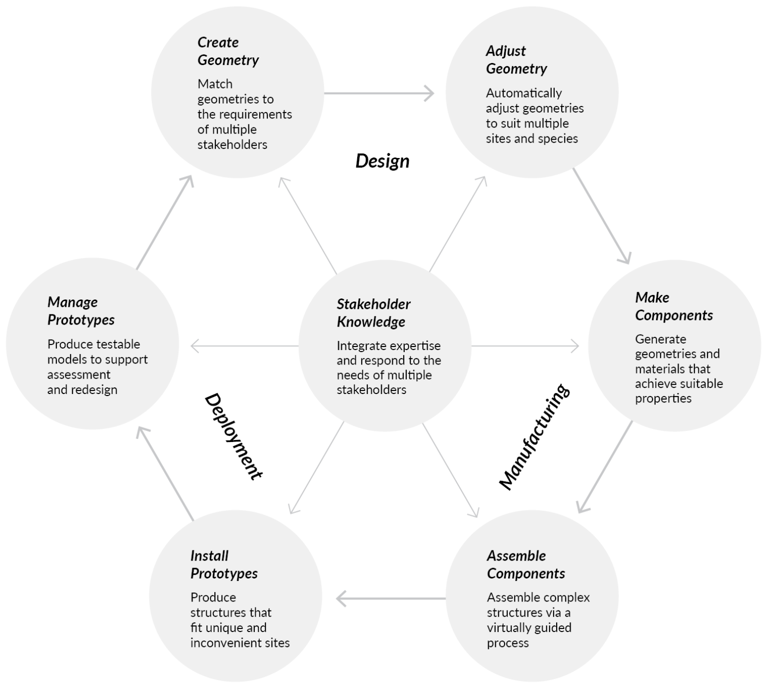


Figure 1. An overview of the proposed workflow which uses computer-aided design and manufacturing for creating artificial cavities.

3 Case-study application: The powerful owl

We illustrate the value of the proposed computer-aided design and manufacturing approach (Figure 1) through a case-study which provided artificial cavities for the powerful owl, *Ninox strenua.* The powerful owl is a nocturnal raptor that inhabits a range of habitats in south-eastern Australia, including relatively undisturbed forests and urban environments (Bradsworth et al. 2017; Isaac et al. 2013). Powerful owls are listed as threatened in the southern parts of their range (Department of Environment, Land, Water and Planning 2019), where the loss of large, cavity-forming trees is the primary negative impact (Isaac et al. 2014). It can take several hundred years for trees to form cavities large enough for powerful owl breeding (Cooke et al. 2018). Artificial cavities offer a possible conservation response (Isaac et al. 2008) but existing structures prove inadequate: only one pair of powerful owls has ever bred in a nest box (on one occasion in 2007) and only one of their two chicks survived (McNabb and Greenwood 2011). Therefore, our aim to develop more effective designs for powerful owls provided a usefully challenging case to address the shortcomings of existing cavity creation.

To test our proposed approach against alternative methods of providing cavities for powerful owls, in 2019, we installed a selection of cavities and compared their performance: two nest boxes, two carved logs, and three computationally designed cavities (see Table S2 in supplementary materials for a summary of the deployed cavities). Each cavity was of a similar size and located in areas of Melbourne, Australia, where powerful owls were nearby but lacked suitable nesting sites. We carried out this project with the appropriate ethics approval from the Faculty of Science Animal Ethics Committee, University of Melbourne (#1914736).

3.1 Design phase

3.1.1 Create geometry using generative design

We used attributes of successful nesting sites, including tree cavities and arboreal termite mounds, to inform the resulting generative designs. In tree cavities, these features include a landing lip, a feeding platform, a climbable exit, and an interior suitable for scratching (McNabb and Greenwood 2011). Termite nests were also relevant as precedents because, unlike decay-induced cavities, they can occur on sufficiently large but young trees. Cavities in such nests achieve adequate thermoregulation, drainage, and ventilation through orientation, varying wall thicknesses, complex surface textures, and internal chambers (Korb 2011). The generative design workflow used Rhinoceros 3D (Robert McNeel & Associates, version 6) software for modelling and Grasshopper 3D (*ibid.*) for visual programming to generate several models that reflected these precedents (see one of them in Figure 2). Generative design helped to produce variable designs that – like tree cavities and termite nests – come in many context-specific geometries and sizes. Developing and testing multiple options is important in the case of owls because humans do not know the optimal geometries of habitat structures. We shortlisted designs that were similar to (1) geometries, proportions, and stepped interiors of tree-cavity entrances, and matched their (2) porosities, undulating geometries, and the ability to wrap around host structures (for details on the specific design techniques, refer to Figures S1–10 in supplementary materials).

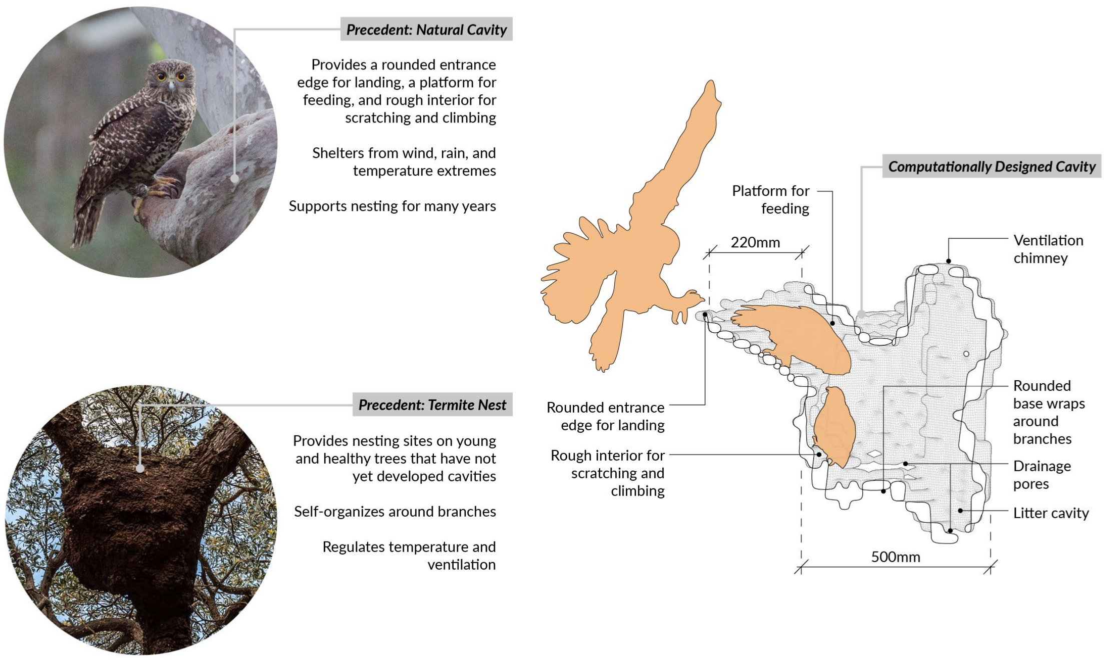


Figure 2. Generatively designed cavity based on natural precedents. Diagrams by the authors. Owl image by Richard Jackson. Termite nest image by Blantyre.

3.1.2 Adjust geometry using parametric modelling

We adjusted the shortlisted cavity designs to suit the requirements of powerful owls and human stakeholders using parametric modelling (Figure 3) (for more information on powerful-owl needs, refer to Table S1 in supplementary materials). The parametric workflow:

1) Adjusted the base geometry to match the proportions and dimensions of natural cavities used by powerful owls. We selected a large size (800x500mm) to accommodate the typical family size of two parents and two young (McNabb and Greenwood 2011).

2) Deformed the base geometry to approximate the appearance and affordances of the natural habitat precedents. We selected broad undulations to match the way tree cavities and termite nests allow owls to enter, exit, and move about the nest more easily.

3) Edited the entrance diameter, angle of protrusion, size of taper, and edge thickness to support the target species' size and behaviour on arrival. We selected similar geometries and sizes (at least 100–200mm) to the entrances of natural cavities that owls use to land, perch, and feed (Gibbons and Lindenmayer 2002).

4) Subtracted the geometry of the target host-structure (in this case, the tree) from the cavity model. For this case-study, we selected living trees instead of buildings or infrastructure, based on advice from ecologists and arborists.

5) Specified components for manufacturing by subdividing the cavity into modular blocks and estimated the amount of human labour and the volumes of building materials required. We adjusted the size of these blocks such that they were small enough for owls to scratch and climb without creating an excessive number of modules to assemble.

6) Modelled a knotted harness in consultation with arborists and engineers to assist with installation and ensure structural stability. The harness compresses the model, distributes structural loads, and provides multiple lifting and fixing points. It can incorporate adjustments for different cavity geometries, aesthetic preferences, and material constraints.

See supplementary materials for the Grasshopper 3D file, a how-to-use guide, and further details on the workflow.

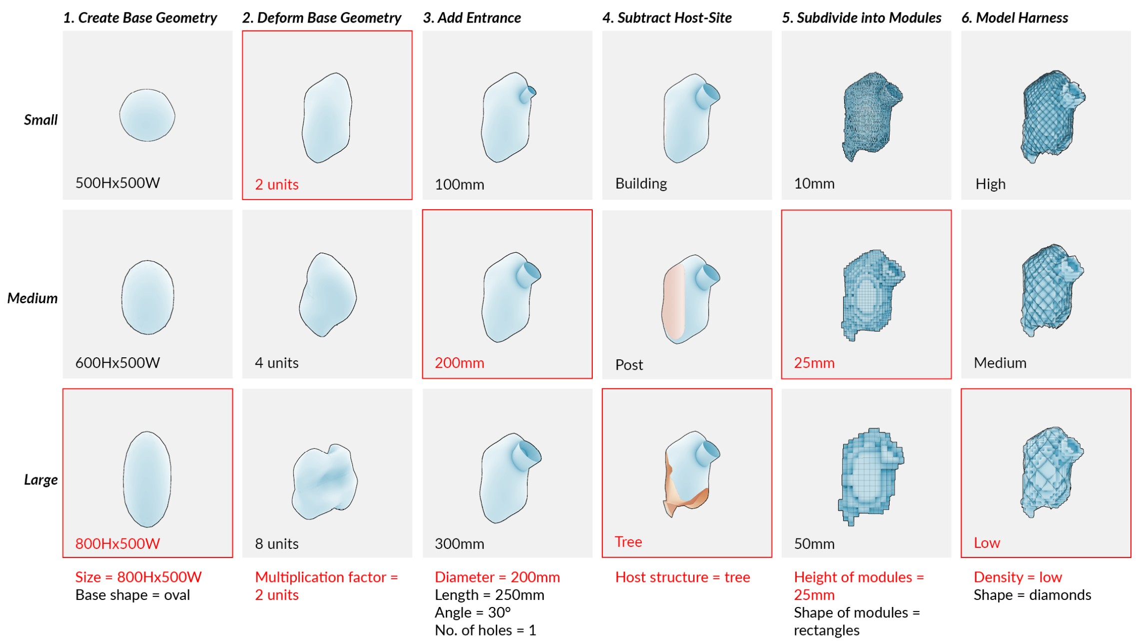


Figure 3. The search space for form-finding and parametric adjustments. Columns: steps generating geometry. Top row: adjustable parameters. Grey rows: examples of options. Red frames: chosen options. Image by the authors.

3.2 Manufacturing phase

3.2.1 Make components using 3D printing

We made modular components of the cavities using two different computer-aided manufacturing techniques: 3D printing and computer-numerical-control (CNC) cutting that can precisely control grinders, lathes, turning mills, and machines. For each technique, we sought materials that could withstand owl scratching, chewing, and defecation without detriment to the inhabitants' safety or the cavity's function. We produced 3D-printed wood modules using

ColorFabb's WoodFill filament, which supported flexible prototyping, integrated jointing mechanisms, and achieved the desired density, porosity, and surface texture (Figure S5 in supplementary materials). To demonstrate the flexibility of our approach, we also tested CNC-cut wood-cement modules (Lohas Australia) covered by a hempcrete mixture (Hemp Building Company). We selected wood-cement for its good strength-to-weight ratio, good porosity for drainage and ventilation, and ease of cutting into variable geometries and sizes. Hempcrete bounded the assembled components to create a strong and durable shell. Hempcrete provided a non-toxic, fire- and termite-resistant, insulative, moisture-repellent, and carbon negative material (Jami, Karade, and Singh 2019). All materials we selected were biodegradable, had temperature- and humidity-buffering qualities, and resembled the colour, texture, and resilience of bark.

3.2.2 Assemble components using augmented reality

To assemble the shells of the artificial cavities, we used augmented reality techniques. We used the Fologram app, available on Microsoft's HoloLens headset and everyday smartphones, to guide the placement of each module by overlaying computer models onto physical objects (Figure 4a). We developed an algorithm to simplify construction, reduce assembly times, and integrate modules with varying surface characteristics, porosity, and drainage capabilities. Optimising the artificial cavity models into modules of 1, 2, 4 or 8 cubes resulted in fewer 'building blocks', thereby making assembly faster and easier (Figure 4b–c). The procedure can work for any geometries, sizes of cavities (100–1000mm), and number or dimensions of modules (see Figure S6 in supplementary materials). The final task of manufacturing involved the fitting of the knotted harnesses. Our computer model and augmented-reality template helped with the harness-making, which involved tying simple overhand knots and did not require specialised labour. These harnesses met strict arborist regulations which require fixing mechanisms to withstand loads of at least seven times the weight of a cavity.

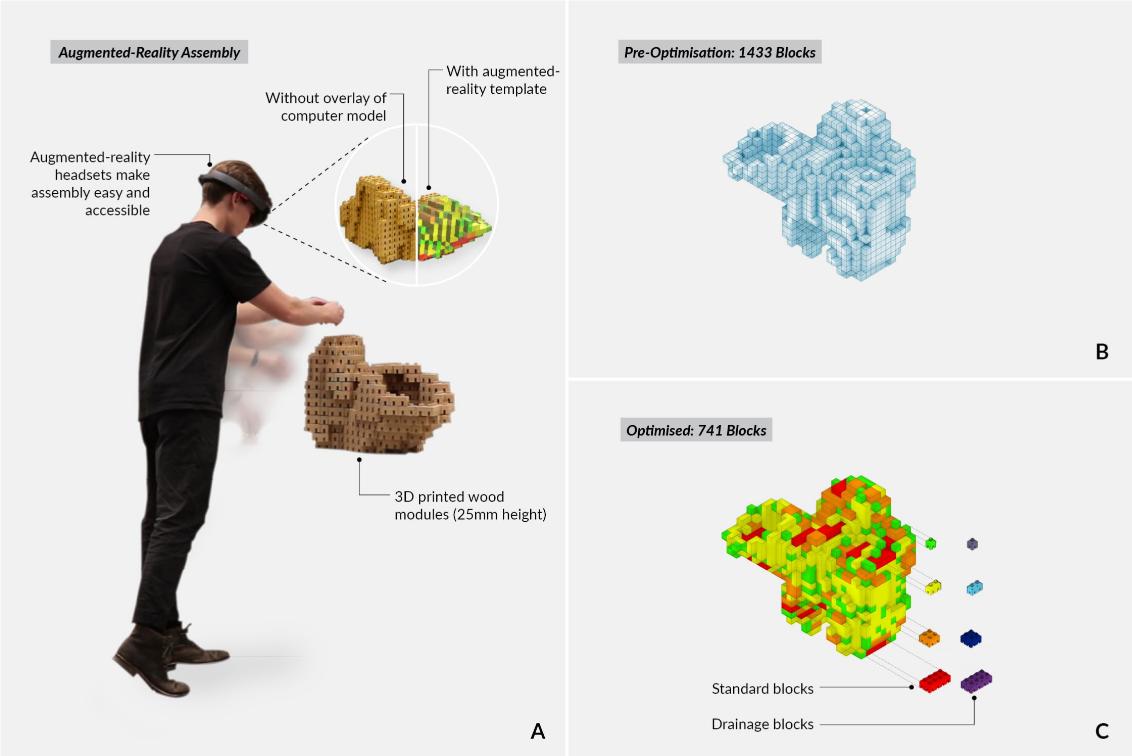


Figure 4. Augmented-reality assembly of a computationally designed cavity and the point-of-view vision of the digital overlay (A), and a computationally designed cavity before (B) and after (C) applying the optimisation algorithm (developed by Alex Holland). Image by the authors.

3.3 Deployment phase

3.3.1 Install prototypes using 3D scanning

We obtained point clouds of the installation sites using a stationary LiDAR scanner to fit the cavities at suitable areas on host trees (Figure 5a). Point clouds are collections of data points that represent locations on the surfaces of physical objects. Using point-cloud processing algorithms in CloudCompare (Daniel Giradeau-Montaut, version 2.1) and Grasshopper 3D, we converted the scanned point-clouds to surface representations (or 'meshes') (see Figure S7 in supplementary materials). In Grasshopper 3D, we positioned the cavity models at preferred attachment locations and subtracted the tree-mesh geometries from the cavities (Figure 5b). The attachment locations took into account the usual nesting sites for powerful owls at 8–40m above ground (Goldingay 2009), advice to install cavities at south-east facing entrances (Government of South Australia 2011), and arborist preferences to place cavities at crotch junctions.

Before installing onsite, we assessed each cavity offsite to ensure structural and thermal safety. These assessments used data loggers (Hygrochron iButton DS1923, iButtonLink) to record temperature fluctuations within a carved log, a nest box, and a hempcrete cavity across four days (June 2019). Each cavity was in the same location, exposed to direct sunlight, and sealed off from potential inhabitants. We tested the installation procedures by building full-scale prototypes (Figure 5c), ensuring that materials and fixing methods were sturdy and durable. We also used small-scale prototypes to discuss ideas with stakeholders and give instructions on installation (Figure 5d). Finally, arborists installed the nest boxes, carved logs, 3D-printed cavity (Figure 5e), and hempcrete cavities (Figure 5f). We compared the time and techniques required to install each cavity (see Figure S8 in supplementary materials for detail on the installation procedures).

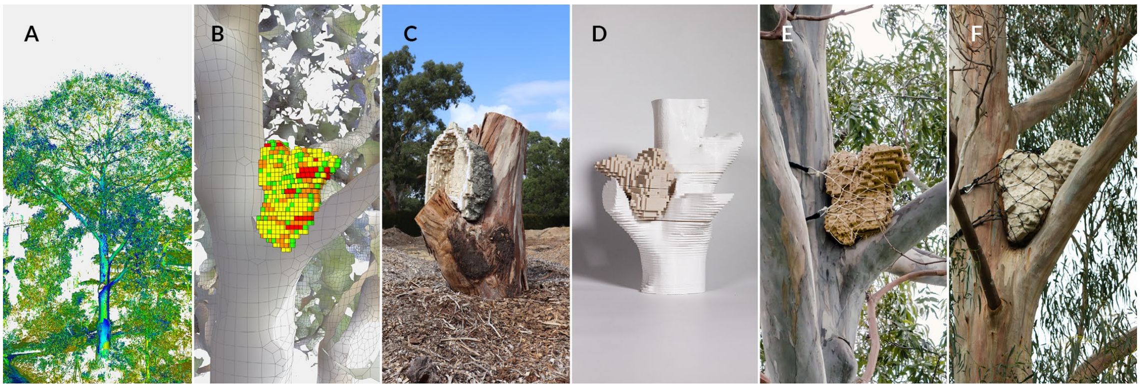


Figure 5. A 3D scanned point cloud of the site (A) and a computationally designed cavity on the surface representation of the host tree (B), a full-scale prototype (C), a small-scale prototype (D), and the onsite installation (E) of a computationally designed cavity. Image by the authors.

3.3.2 Manage prototypes using data-driven design

The final stage of our pilot study used data-collection devices to evaluate environmental performance and offer insights into redesign of the cavities. To compare microclimate performance, we fitted data loggers (iButtons) into each nest box, carved log, and computationally designed cavity and recorded seasonal variations (for 172 days from July 2019 to January 2020). We developed 3D-printed holders to secure and protect the data-logging devices from damage (see Figure S9 in supplementary materials). Our aim was to make these holders smaller, less intrusive, easier to reproduce, and able to accommodate a variety of devices. We assessed animal visitations through bi-monthly observations, automated sound recordings using AudioMoths (Hill et al. 2019), and monthly analyses of nest detritus (August to December). This monitoring forms part of a longer-term ongoing evaluation of ecological responses. The resulting climatic and observational data can inform our computer models and physical prototyping to alter material selection, thickness, geometry, and size of future cavity iterations (Figure 6).

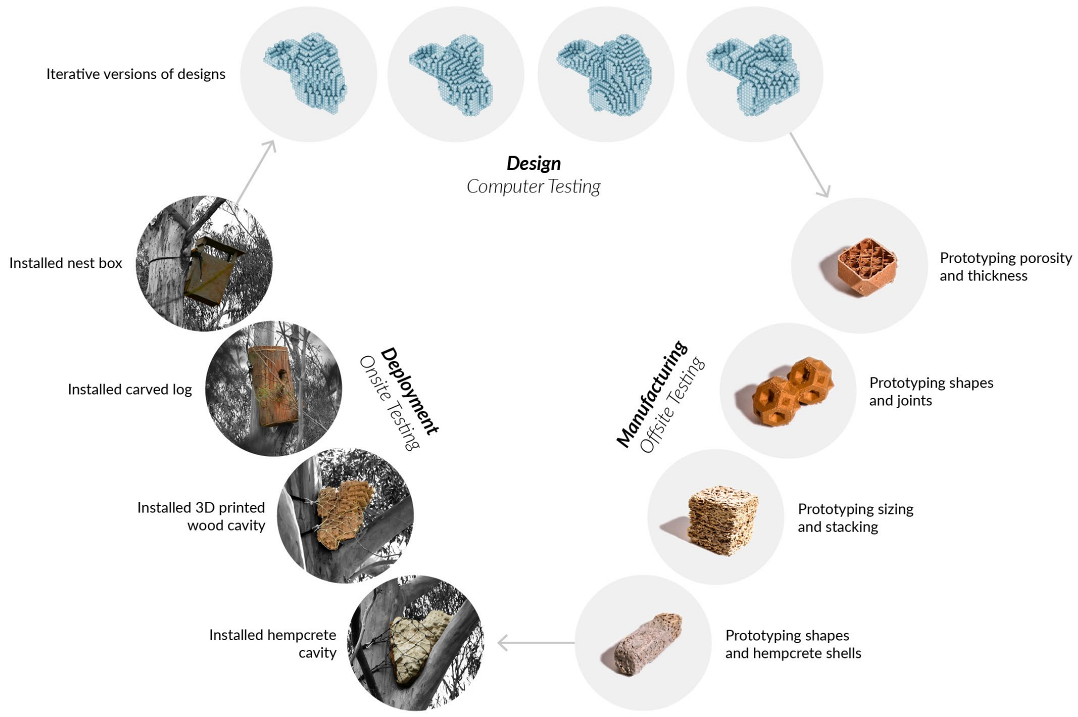
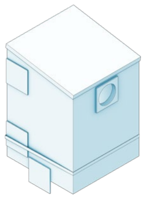
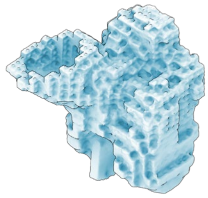


Figure 6. Illustrated process for assessment and redesign of prototypes. Top: design and computer-modelling potential for iterative development of cavities. Left: deployment and testing of cavities onsite. Right: manufacturing and prototyping of cavity components offsite. Image by the authors.

3.4 Preliminary evaluation of performance

Table 2 summarises the preliminary outcomes of the stages above according to our initial criteria (Table 1), comparing computationally designed cavities with nest boxes and carved logs. We observed possible prey of powerful owls using our designs, including the common ringtail possum (*Pseudocheirus peregrinus*) and rainbow lorikeet (*Trichoglossus moluccanus*), but no owls visited the host-sites. These comparisons are based on short-term evaluation from a small pilot study but show the possibilities of performance monitoring (see Table S2 in supplementary materials for a summary of the deployed cavities).

Table 2. Comparison of nest boxes, carved logs, and computationally designed cavities for powerful owls, *Ninox strenua*.

Method	Nest Boxes	Carved Logs	Computationally Designed Cavities
Typical structure			
Design			
Approximation of natural structure	Low: did not include affordances such as the rough interiors for scratching/climbing, protruding entrance tunnels for landing/feeding, and context specificity of natural precedents	High: achieved similar materials and internal textures to natural precedents but did not include protruding entrance tunnels or context-specificity	Moderate/High: computer modelling integrated geometries that approximate the appearances and affordances of tree cavities and termite nests
Diversity of geometries	Low: supplier offered two different but similar options of nest box designs, with other similar options available from other suppliers	High: log geometries were unique but not scalable	High: generative design produced many design options that were customizable and scalable
Capacity for modification	Low/Moderate: possible adjustments to boxes were limited to entrance size, cavity dimensions, and materials	Low: possible adjustments to log geometry, size, proportions, and material were limited	High: parametric design supported incremental adjustments to entrance and cavity geometry/size, construction techniques, and fixing mechanisms
Manufacturing			
Availability of materials	High: materials ($300–400) were purchasable locally, off-the-shelf, and online	Low/Moderate: logs ($525) that were large enough were difficult to find	Moderate: 3D printed wood materials ($1050) were available on demand but shipped from abroad; wood cement and hempcrete materials ($450) were purchasable locally
Sustainability of materials	Moderate: plywood was non-toxic and renewable but heavily processed	High: most materials were organic, non-toxic, renewable, and locally sourced	Moderate: use of 30% recycled wood in 3D printed cavity improved on nest boxes that use 100% plastic; use of hemp/wood in hempcrete cavity improved on nest boxes that use 100% cement

Ease of construction	High: simple structure made for easy and fastest assembly (0.25 days)	Moderate: edits to structure (i.e., drilling larger holes and capping ends) made for slower assembly (0.5 days)	Moderate/High: use of augmented-reality headsets made for easy but still slower assembly (1 day for 3D printed; 2 days for hempcrete)
Deployment			
Ease of installation	Moderate: lightweight structures (20kg) were easy to hoist but difficult to accurately position on complex tree geometry, and fast to install (0.2 days)	Low: heavy structures (250+kg) required trucks to hoist, were difficult to position, and slowest to install (0.3 days)	High: lightweight structures (15kg for 3D printed; 40kg for hempcrete) were easy to install (confirmed by arborists), and fastest to install (0.1 days)
Minimization of impact on installation sites	High: angled supports allowed for tree growth; padded backing provided a soft buffer between tree and cavity	Low/Moderate: required pruning of branches to create a placement platform	High: did not damage the tree; coconut fibre backing provided a soft buffer between the tree and cavity
Lifespan	Low/Moderate expected but to be confirmed	High expected but to be confirmed	Moderate/High expected but to be confirmed
Microclimate conditions	Low: experienced largest temperature fluctuation (0.5-42°C)	High: experienced least temperature fluctuation (4.5-33°C)	Moderate: experienced moderate temperature fluctuation in hempcrete cavity (2-37.5°C); 3D printed cavity was located separately from other cavities (2.5-42.5°C)
Use by target species	Low: feathers found inside but no use by species observed; no powerful owls visited the host-sites	Moderate: supported prey base of powerful owls (Crimson rosella (*Platycercus elegans*); Galah (*Eolophus roseicapilla*) but no powerful owls visited the host-sites	Moderate: supported prey base of powerful owls (Common ringtail possum (*Pseudocheirus peregrinus*); Rainbow lorikeet (*Trichoglossus moluccanus*) but no powerful owls visited the host-sites

4 *Towards systematic innovation for wildlife conservation*

We have presented a framework to guide the use of advanced design techniques to create artificial cavities for wildlife conservation. At each stage of the workflow, we provide examples and references that can aid researchers in the fields of ecology and conservation to engage with the capabilities of design. This understanding can help to facilitate collaborative teams to work on conservation initiatives which draw on the expertise of scientists, designers, engineers, local human residents, and others. Our pilot study on nesting cavities for powerful owls demonstrates opportunities for computer-aided design and manufacturing techniques to enhance the design of artificial cavities. The ability to adjust design parameters results in a workflow that can respond to a variety of other species, scales, stakeholders, and installation sites. This flexibility and broad applicability demonstrate the promise for computer-aided design and manufacturing to benefit future artificial habitat-structures through geometric innovation, novel construction techniques, and iterative exploration (Table 3).

Table 3. Benefits and limitations of computer-aided design and manufacturing methods for artificial cavity creation.

	Design Phase		***Manufacturing Phase***		***Deployment Phase***	
Stages	Create Geometry	Adjust Geometry	Make Components	Assemble Components	Install Prototypes	Manage Prototypes
Techniques	Generative design	Parametric modelling	3D printing	Augmented-reality assembly	Laser scanning	Data-driven design
Benefits of technique	Ability to find geometries that match criteria, and geometries of target habitat structures, such as natural cavities	Ability to automatically produce new versions and adjust designs to suit different sites, species, and stakeholders	Ability to generate geometries and textures that approximate material properties of natural cavities	Ability to easily assemble complex structures through virtually guided assembly	Ability to produce precisely fitting structures and improve ease and precision of installation	Ability to test and redesign models in simulations or in the field
Limitations of technique	Some criteria are unknown or hard to express numerically	Algorithmic recipes also have limited flexibilities. Multiple recipes might be necessary.	3D printing can be slow and relatively expensive	Modular designs require additional time for assembly	Laser scanning is an additional step in the process	It can be difficult to isolate the impact of design features on simulated or actual use

4.1 Design innovation

4.1.1 Ability to approximate natural geometries

Computer-aided design can approximate complex characteristics of natural tree cavities, defining natural geometries that are not possible through 2D drafting. Our case study shows how computationally designed cavities can approximate the appearances and affordances of natural cavities and termite nests through varying edge thicknesses, internal textures, protruding entrances, and precise fitting to host sites. The ability of computer-aided design to integrate the needs of multiple stakeholders proves useful to balance the requirements of both humans and other animals. For example, our form-finding process shows how computational modelling can consolidate information on target species' behaviours such as feeding or climbing and human production-practices such as standardisation of components for assembly. Further morphological analysis of complex habitat structures may improve the understanding of natural precedents and inform better targets for design. For example, computer tomography (CT scans) of tree cavities could provide volumetric and statistical benchmarks for artificial cavities. Future analysis of cavity shapes should draw from the different complexity measurements of artificial habitat-structures in marine environments (Bishop et al. 2022). This capacity to match geometric and functional properties of habitat structures can benefit designs that aim to suit other species and resemble, for example, rocks, bark, and burrows.

4.1.2 Flexibility to respond to different sites, species and stakeholders

What opportunities do these computational approaches present for further accessibility and outreach? Our adjustable parametric workflow can produce designs that respond to diverse sites and species (see Figures S1–10 in supplementary materials). Future possibilities for deployment are evident through the examples of online configurators for customised shoes, jewellery, or toys (Sinclair, Campbell, and Yavari 2014). In the context of artificial habitat-structures, an online configurator could provide flexible, do-it-yourself approaches for conservation practitioners and community members. Extensions of the algorithms in our workflow can support customisation of habitat structures in response to location, available materials, choice of host structures, target species, willingness to assemble the design, budget constraints, and access to tools. Such algorithms also have the capacity to integrate numerical data that represent the preferences of target species, abiotic factors such as wind, gravity, humidity, or solar exposure, and other constraints to form a variety of geometries that suit different climates, species, and behaviours (see Figure S10 in supplementary materials). These computational workflows allow for informed and automated reuse of scientific and technical knowledge, making advanced designs significantly more accessible.

4.2 Manufacturing innovation

4.2.1 Use of diverse, advanced materials

A key advantage of computer-aided manufacturing is the ability to produce and explore a wide range of novel materials. Our pilot study demonstrates that 3D printing can integrate materials that match the performance of naturally occurring habitat structures and balance the needs of stakeholders. For example, prototyping of geometry, thickness, and porosity helps to find appropriate strength and scratch-resistance for inhabitants while minimising material use and weight to ease installation by arborists. The exact lifespans of our prototypes are unknown, but we expect the materials to last longer than many wooden nest boxes. Possible limitations of 3D printing include time and cost. Restricted access to printers makes 3D printing slower than plywood construction of typical nest boxes but still considerably faster than decay-induced cavity formation. Larger-scale production can increase efficiency by utilising existing facilities that produce multiple components in parallel (e.g., printing farms). Further, while we focused on 3D printing, computer-aided manufacturing offers many other techniques and innovative materials that allow fast and cost-effective production. For instance, CNC-cut wood-cement and hempcrete are more readily available and can shorten manufacturing times while still providing geometric flexibility. Beyond these techniques and materials, there are many other computer-aided manufacturing methods that could build wildlife habitat-structures, including robotically extruded clay (Kontovourkis and Tryfonos 2020), drone-operated mud-sprayers (Chaltiel, Veenendaal, and Verzura 2019), and 3D-printed aggregations of sticks (Yoshida et al. 2015).

4.2.2 Assisted assembly of complex geometries

It is important that methods for constructing artificial cavities are practical and accessible. Although technologies in our approach like augmented reality headsets are uncommon in conservation ecology and may initially appear complicated, other practical trials demonstrate that such techniques have user-friendly designs and allow non-experts to assemble objects without prior training (e.g., see the bricklaying of architecturally-designed walls, Jahn et al. 2019). Similarly, the use of 3D printing might appear time-consuming. However, the resulting interlocking modules aid assembly and negate the need for additional adhesives. Like toy building-bricks, the modular approach results in easily adjustable configurations that produce stable structures. This reliability, flexibility, and ease of assembly is especially beneficial when compared with carved logs, which rely on the opportunistic sourcing of felled and fallen logs and take up to a day to prepare. While still unusual, the use of computer-aided manufacturing technologies is already intuitive and will become more accessible in the future.

4.3 Deployment innovation

4.3.1 Easier installation at challenging sites

Habitat structures are often difficult to install at ecologically relevant locations, for example, high in trees, or on complicated structures. Our computationally designed cavities can weigh less than conventional nest boxes or carved logs and precisely fit tree junctions. Consequently, arborists find them easy and quick to hoist, manoeuvre, and install. By contrast, the other cavities in the pilot study present several installation challenges. Nest boxes are difficult to stabilise in the required orientation, while carved logs physically damage trees when arborists cut the host branch into a stump for additional weight-support. Further, the large weight of carved logs requires stronger attachment systems and the use of machinery for hoisting. These requirements add considerable time to installation procedures and preclude the use of less accessible sites. By assisting the installation of habitat structures in locations with difficult access, computer-aided design and manufacturing can support conservation in a wider range of places.

4.3.2 Openness for improvement through prototyping, evaluation, and iteration

Successful conservation outcomes rely on ongoing monitoring and accountability (Woinarski 2012). Our approach demonstrates that computer-aided design and manufacturing can facilitate continual assessment and redesign through flexible feedback loops of computer modelling, offsite testing, and onsite monitoring. This allows for incremental improvements to designs with degrees of flexibility and precision not possible with alternative methods. Importantly, we argue for evaluation against a broader range of criteria than are typically considered. Our approach takes into account the needs of the target species, the human stakeholders, the installation site, and the overall sustainability of artificial cavities.

Stable and mild microclimates within cavities are critical for their ability to support nest selection, breeding success, and survival (Rowland, Briscoe, and Handasyde 2017). Comparative performance data can inform the material and geometric choices of future cavity iterations through adjusting the appearance, weight, porosity, and other characteristics (see Figure S5/9/10 in supplementary materials). Preliminary investigations suggest that the thermal performance of hempcrete cavities is considerably closer to that of carved logs than nest boxes and 3D-printed cavities (unpublished data, see Table S2 in supplementary materials). This reiterates the need for research which prototypes alternative geometries and materials, tests their performance, and adjusts future designs accordingly. Such testing can be cheaply and efficiently conducted offsite by simulating the heat produced by occupants (see Kearney et al. 2011). The need for suitable microclimates and gradual improvements in response to habitation is a familiar problem to architects and designers. Prototyping which utilises computer-aided design and manufacturing presents promising opportunities for further research.

Finally, evaluations of wildlife responses to artificial cavities are critical to determine if such structures are performing as expected and meeting conservation goals. Our initial assessment was limited to small-scale, short-term investigations of microclimate and visitation by wildlife as part of a proof-of-concept trial. A necessary next step involves deploying a larger number of cavities, accompanied by longer-term, population-level assessments, ideally in tandem with experimental design (Cowan et al. 2021). Long-term monitoring of visitation and nesting success is particularly important, as it may take species such as powerful owls several years to habituate to and nest in artificial structures. Given the novelty of the design and approach, a better understanding of the behavioural response of species to these artificial cavities is also important. As such, we have recently equipped a 3D printed wood cavity with a camera trap as well as temperature, humidity, and air quality sensors that can support live online monitoring. We anticipate that this monitoring will inform further designs and help to assess the benefits of the proposed workflow.

5 Conclusions

This article provides a framework for the computer-aided design, manufacturing, and deployment of habitat structures for cavity-dependent animals that are versatile and can accommodate a broad range of habitat requirements. Through a pilot study that designs cavity structures for powerful owls, we show that computer-aided design and manufacturing can make substantial improvements to conventional approaches. Despite involving complex geometries and novel materials, our designs are easy to construct and install. The computational approaches in this article can make advanced designs accessible to non-specialists and support accountability and systematic innovation through numerical comparison, integration of evidence, and ongoing prototyping. These reusable workflows can aid in the tasks of practical conservation and support ecological research by effectively negotiating the needs of both humans and target species. Each stage of the workflow allows researchers in the fields of ecology and conservation to understand the capabilities of design and use this understanding to aim for more effective conservation outcomes. Significantly, the computational approaches in this article can support better design decisions in complex and uncertain situations. The outcomes are applicable in many situations and have the potential to result in better performing designs.

6 Supplementary materials

For published article and Supporting Information (at bottom of page), see: https://doi.org/10.1111/2041-210X.13806

7 Author contributions

Dan Parker and Stanislav Roudavski conceived the ideas, designed methodology and designed prototypes. Dan Parker constructed the prototypes, conducted field testing, and led the writing of the manuscript. Kylie Soanes and Therésa Jones led the ecological study design. Nick Bradsworth and Bronwyn Isaac provided input regarding powerful owl ecology, behaviour, and spatial distribution. Marty Lockett provided field assistance in installing and monitoring the cavities. All authors contributed critically to the writing and revision of the manuscript and gave final approval for publication.

8 Acknowledgements

We respectfully acknowledge the Wurundjeri people who are the Traditional Custodians of the Land on which this research took place. The project was supported by research funding from the Australian Research Council Discovery Project DP170104010, Future Cities Grant (Melbourne Sustainable Society Institute) and William Stone Trust Fund (University of Melbourne). We thank Knox City Council, Melbourne Tree Care, NextLab, The Hemp Building Company for in-kind support. Also, thanks to Alex Holland, Professor Brendon McNiven, Jim Greenwood, Judith Alcorn, Julian Rutten, Rebecca Rasmussen, and Tim Uebergang for the expertise and guidance on early stages of this project.

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Chapter 5. Which Design Is Better? A Lifecycle Approach to the Sustainable Supply and Replacement of Artificial Habitat-Structures

Dan Parker, Stanislav Roudavski, Chiara Bettega, Luigi Marchesi, Paolo Pedrini, Mattia Brambilla, and Kylie Soanes

Abstract

This article presents a lifecycle approach to designing and assessing artificial tree-hollows for wildlife conservation. Artificial hollows are an increasingly common conservation strategy in response to habitat loss from land use changes, forestry, agriculture, and disturbances such as wind or fire. However, the effectiveness of artificial habitat-structures is often questioned. There is a need to develop methods for design and assessment that consider broader environmental, logistic, and economic implications. We propose a novel approach that integrates biological and technological lifecycles to enhance the implementation of artificial hollows. This study developed and compared diverse prototypes made from laser-cut timber, 3D-printed plastic, and mycelium assembled using augmented reality. We assessed the performance of each prototype across multiple installation cycles in a storm-damaged forest by estimating their cumulative carbon emissions, energy use, costs, and waste production. The results indicate that design choices significantly influence the environmental impact of artificial hollows, highlighting the need for strategies that optimise ecological benefits, consider sustainability, and are sufficiently flexible to meet local conservation requirements. Our findings emphasise the need to preserve forests and advocate for better standards in support of design. The lifecycle approach can apply to many ecosystems and make conservation management more accountable and sustainable.

1 Introduction

Globally, thousands of species depend on tree hollows for shelter and reproduction (Hoek, Gaona, and Martin 2017). Many animals cannot excavate their own hollows and rely on cavities made by woodpeckers, termites, or decay-causing organisms (Newton 1994; Trzcinski et al. 2021). These natural tree hollows can take decades or even centuries to develop (Vesk et al. 2008). The loss of hollow-bearing trees can introduce gaps between the disappearance of existing hollows and the emergence of new ones (Manning et al. 2012). Resulting hollow scarcity puts dependent species at risk of population decline and even extinction (Penton et al. 2021). Today, hollows are in short supply in many places due to the abandonment of traditional silviculture, the intensification of agriculture, the growth of managed forestry (Sebek et al. 2013), and urban encroachment (Davis, Major, and Taylor 2013). In response, conservationists provide anthropogenic ('human-made' or 'artificial') hollows, with varying and sometimes unknown effectiveness for biodiversity (Littlewood et al. 2020; Dicks et al. 2021). For example, nest boxes can provide critical habitat structures for birds (Stojanovic et al. 2023) and mammals (Goldingay, Rohweder, and Taylor 2020) when the supply of natural hollows is absent or insufficient (Cockle, Martin, and Drever 2010). However, some designs and placements have negative effects on bird health and reproduction (Zhang et al. 2023). Furthermore, expensive and sometimes ineffective implementations call into question investments in nest boxes (Le Roux et al. 2016; Lindenmayer et al. 2017; Rueegger et al. 2019; Brown, Jones, and Scanlon 2021; McKenney and Lindenmayer 1994; Le Roux et al. 2015).

Beyond economic considerations, there is a need to consider the environmental impacts of artificial hollows because demand is likely to increase. For example, there are plans to create one million hollows in fire-damaged forests in Australia (Luu 2021) and 300 million plastic hollows on utility poles in the United States (Schultz 2018). There are already several million nest boxes within domestic gardens in the United Kingdom (Davies et al. 2009). Further research is necessary to understand the impacts of such large-scale interventions. Some studies estimate the economic costs of nest-box programmes over 150+ years (Spring et al. 2001; McKenney and Lindenmayer 1994). Others have looked at sustainable materials (Gunnell, Williams, and Murphy [2010] 2019) including recycled plastic (McComb et al. 2021), salvaged industrial pipes (Groom 2010), and repurposed packaging (González-García et al. 2011). However, to our knowledge, systematic modelling of both environmental and economic implications across options is not available. For example, what are the consequences of installing hundreds of plywood boxes that break after a few years versus plastic alternatives that may not biodegrade for centuries? This article responds to calls for better deployment of artificial hollows (Cowan et al. 2021; R. D. Crawford and O'Keefe 2024) that ensures long-term planning and management on landscape scales (Manning et al. 2012; Thompson, Keenan, and Kelly 2023; Valera et al. 2019; Gibbons and Lindenmayer 1996).

We consider how a 'lifecycle approach' can inform the design and assessment of artificial hollows. As a working definition, the approach integrates biological and technological understandings of lifecycles to develop a sustainable supply of habitat-structures, whether natural or artificial (Figure

1). In biology, the concept of lifecycle (cf. life history and ontogeny) describes the life of an organism across stages that might include a single fertilised cell, growth and development, maturity, reproduction, senescence, and death (Bonner 1993). A better understanding of such biological lifecycles can usefully inform design processes that seek to support biodiversity (Weisser and Hauck 2017; Temmink et al. 2021). In design and engineering, lifecycle analysis (cf. cradle-to-cradle and circular economy) helps assess the environmental impacts associated with activities, products, nations, companies, and buildings (Bjørn et al. 2020) across raw-material extraction, material processing, manufacturing, packaging, transportation, distribution, use, reuse, repurposing, maintenance, repair, disassembly, recycling, disposal, and waste management (Curran 1993). Technological lifecycles provide benchmarks for sustainability that go beyond the reduction of harm and can lead to actions that minimise or even eliminate resource depletion, energy use, pollution, and landfill waste (Muralikrishna & Manickam, 2017), while protecting biodiversity (Winter et al., 2017) and restoring ecosystem services (Liu and Bakshi 2019). Production can achieve circularity through biological cycles, where organic materials return to and replenish the biosphere, or through technological cycles, where synthetic materials safely circulate in a closed-loop system of manufacturing, recovery, and reuse system (Kopnina 2018).

Studies have used concepts of lifecycles in forest management and the assessment of artificial habitat-structures, but not in application to artificial hollows (Holland et al. 2023). For example, biodiversity-oriented management of commercial forests considers harvesting cycles next to phases of regeneration, development, and maturity (Kraus and Krumm 2013). In the management of forests intended for wood harvesting, there are models that simulate the biological cycles of natural hollows from the moment they emerge in a tree to their decomposition (Ball, Lindenmayer, and Possingham 1999). The related concept of nest webs connects the biological lifecycles of hollows and species and can inform the management of more resilient and biodiverse forests by modelling the links between hollow producers, such as woodpeckers, with non-excavating users that include many songbirds, ducks, raptors, and other organisms (Ibarra, Cockle, et al. 2020; Martin and Eadie 1999). Cases in marine environments, such as artificial reefs, demonstrate the potential for technological lifecycle assessments to ensure environmental safety through maintenance and responsible decommissioning (Suzdaleva and Beznosov 2021). In the context of terrestrial environments, analysis of long-term lifecycles that combine natural and artificial habitat-structures can inform provision of roosting sites for birds (Holland et al. 2023). Although studies on nest boxes have considered the lifecycles of target species (Stojanovic et al. 2020), the potential value of analysing the lifecycles of hollows themselves has not been explored.

How can lifecycle approaches benefit the design and assessment of artificial hollows? We propose that a lifecycle approach can assist in producing, supplying, and replacing hollows in ways that integrate the benefits of natural and artificial hollows throughout the cycles of material processing, manufacturing, use by wildlife, decommissioning, and possible re-commissioning (Figure 1). Our hypothesis is that a lifecycle approach can usefully inform approaches to implementing hollows by considering:

a. biological cycles of natural hollows including their material properties, rates of recruitment, interspecies interactions during formation, patterns of use, processes of self-sustainment, and change over time including decomposition; and

b. technological cycles of artificial hollows to reveal environmental and economic implications of design options over the long periods and large areas that are necessary to sustain populations.

To investigate the potential of this approach, this article: introduces a design experiment that compares lifecycles of artificial hollows; demonstrates consequences and opportunities of design options, and discusses benefits of a lifecycle approach for human and nonhuman stakeholders.

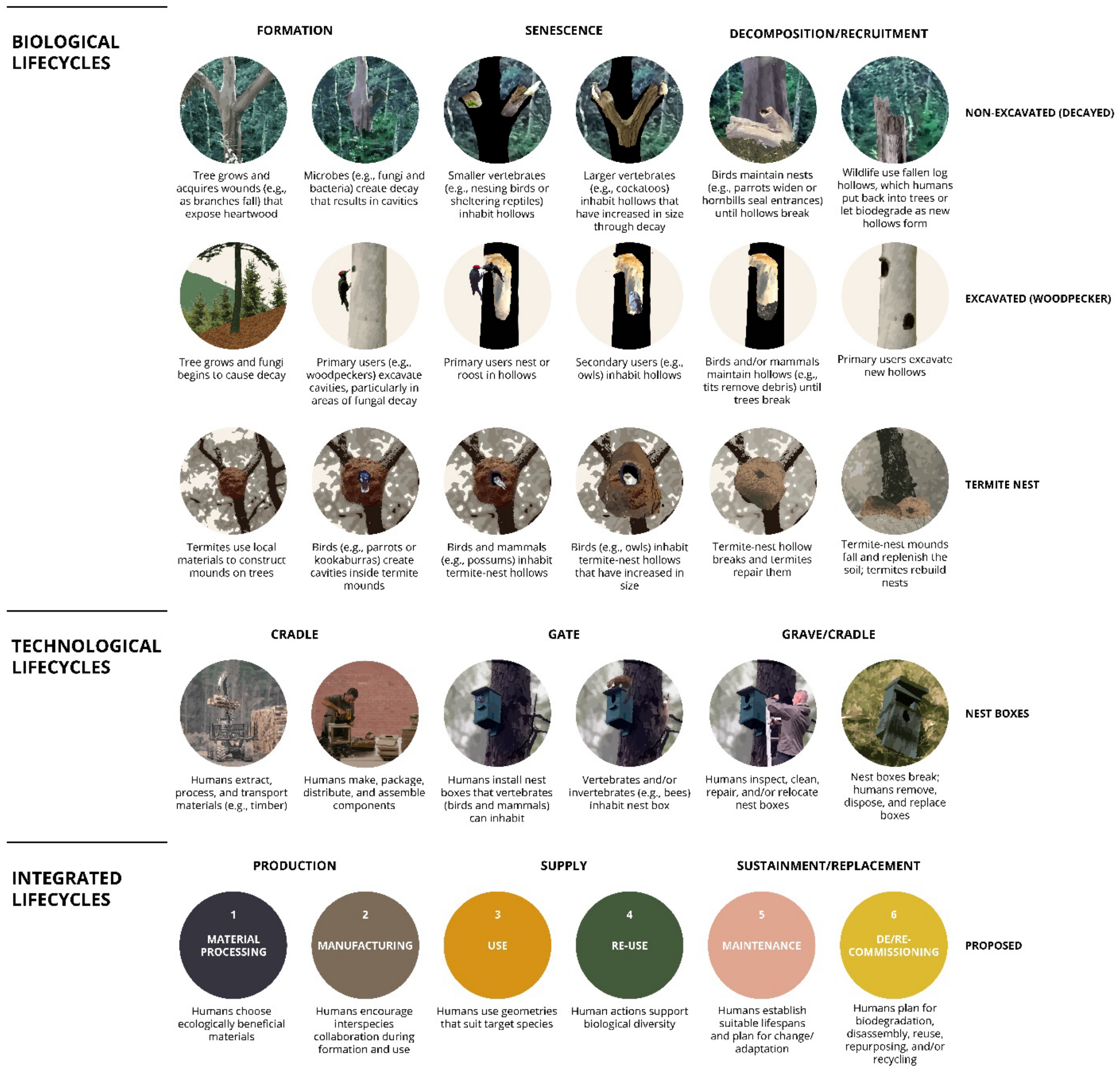

Figure 1. A lifecycle approach that integrates biological and technological understandings of lifecycles, as illustrated through tree hollows. We group stages of each hollow using terms common in the literature. Biological cycles follow stages of formation, senescence, and decomposition or recruitment (top rows). Technological cycles refer to cradle, gate, and grave or back to cradle (middle row). We unite these stages under production, supply, sustainment, and replacement (bottom row), highlighting similarities across stages of material processing, manufacturing, use, re-use, maintenance, and decommissioning or recommissioning (columns). Image by the authors.

2 Methods

We conducted a design experiment to explore how a lifecycle approach can usefully inform ways to supply hollows in large-scale artificial-hollow programmes. This design experiment used (a) precedents of biological lifecycles to propose a design of an artificial hollow, and (b) the analysis of technological lifecycles to evaluate the benefits and feasibility of the proposal. In five steps, the design experiment:

i. focused on an area where ongoing regeneration activities include the deployment of artificial hollows;

ii. developed a novel design proposal for the study area, putting a lifecycle approach into practice;

iii. built prototypes of the proposed hollow using computer-assisted techniques;

iv. estimated the economic and environmental implications of supplying each prototype multiple times to sustain the presence of hollows while the forest regenerates; and

v. compared economic and environmental implications in a realistic scenario of reinstating lost hollows in a reserve within the study area.

2.1 Study area for the design experiment

In 2018, a large windstorm named Vaia hit northern Italy, damaging more than 42,000 hectares of forest (Chirici et al. 2019). We focused on the Trento province, where the storm affected approximately 20,000 hectares (Provincia Autonoma di Trento 2022), consisting predominantly of Norway spruce (*Picea abies*) (Provincia Autonoma di Trento 2019). Our study site was the Paneveggio-Pale di San Martino Natural Park, located in the eastern part of the province. Many of the fallen trees had hollows made by black woodpeckers (*Dryocopus martius*). These hollows provided critical nesting and sheltering sites for several species of birds and mammals (Marchesi et al. 2020). Large-scale regeneration activities and the need for long-term supply of artificial hollows made this study area in Trentino a suitable case study for lifecycle-oriented design.

2.2 Design of artificial hollows using a lifecycle approach

The design offers an approach to reinstate habitat structures on dead trees that had woodpecker hollows before breaking during Storm Vaia or from subsequent post-disturbance logging (Figure 2). We based this design on evidence that defines the properties shared by hollows produced by decay, woodpeckers, and termites (Figure 1). Following the lifecycle approach introduced in Figure 1, we aimed for (1) material processing that is local and organic, (2) manufacturing techniques that involve beneficial interactions between organisms, (3) use by hollow-dwelling vertebrates, (4) re-use by multiple species, (5) maintenance that enables suitable lifespans and adaptation, and (6) decommissioning through biodegradation (Figure 2).

1) ***Material processing***. The design uses mycelium, a material that is becoming more common in architecture, product design, and packaging for its versatile, lightweight, shock absorbing, acoustically and thermally insulating, and sustainable qualities (McGaw, Andrianopoulos, and Liuti 2022; Jose et al. 2021; Manan et al. 2022). Mycelium is the root-like structure of fungi. As a construction material, mycelium grows through and binds

substrates of agricultural waste such as woodchips, hemp, or sawdust (Elsacker et al. 2020). It is possible to source spores or fungal samples on site to grow mycelium through local debris, similar to how termites build nests with soil and other locally available substances (Genise 2017). The use of local strains mitigates the biosecurity risks of introduced species of fungi (van den Brandhof and Wösten 2022) and the use of local substrates reduces resource depletion and pollution (Vandelook et al. 2021).

2) ***Manufacturing.*** The idea of growing an artificial hollow is influenced by the way natural hollows emerge through interspecific interactions. For example, birds including woodpeckers can have symbiotic relationships with decay-causing fungi (Jusino et al. 2016; Elliott et al. 2019). The design uses mycelium-based composites that mould into functional shapes for local species, while allowing the mycelium to thrive. The density of the substrate and/or use of protected coatings can prolong or shorten the life expectancy of the mycelium (Gan et al. 2022), depending on the needs of the site. Our objective to keep the mycelium alive is to match the properties of hollows in living trees that can maintain more stable microclimates than hollows in dead wood (Griffiths, Robert, and Jones 2022; Strain et al. 2021) and to replicate the ability of termite mounds to maintain better conditions for roosting or nesting than those found in abandoned nests (Dechmann, Kalko, and Kerth 2004; Sanchez-Martinez and Renton 2009). Keeping mycelium alive also avoids energy use and emissions from heat-treatment.

3) ***Use***. The goal of the design illustrated here is to support secondary nesters, such as the boreal owl (*Aegolius funereus*), a climate-sensitive species found in the study area (Brambilla et al. 2020). Boreal owls regularly nest in tree hollows excavated by black woodpeckers (Brambilla et al. 2013) but can also use human-supplied hollows (Williams et al. 2021). Our design is inspired by the habitat structures these owls use and features of the study area. The shapes resemble bracket mushrooms that boreal owls sometimes use for roosting and that provide an awning above some hollows (Figure 3). We generate the shapes by adapting an algorithm that mimics the structures of mushroom gills. The gills run horizontally inside the hollow to assist birds climbing, and vertically outside to guide water away from the entrance (Figure 3).

4) ***Re-use***. Another goal of the design is to function in similar ways to woodpecker hollows that support multiple species. For example, one woodpecker hollow can support fungi, bryophytes (Larrieu et al. 2018), and up to seven vertebrate species during its lifespan (Cockle et al. 2019). Our patterns serve this additional purpose to create bio-receptive surfaces for mosses and lichens. To create suitable conditions, moisture-retaining pores congregate in the shadier and wetter areas of the hollows. This process uses computer simulations of water runoff (Catemario di Quadri 2021; Piker 2019) and solar-irradiation analysis (Roudsari and Pak 2013) to locate the damper areas (Figure 3). Through the application of 3D scanning (Parker et al. 2022), the design can fit the shapes of host

structures, enabling analyses that depend on precise positioning and orientation (Figure 2).

5) ***Maintenance***. Maintenance can include adding mycelium to repair damage as well as adding or removing material to adjust the number or entrances, modify their sizes, and alter cavities in response to evidence. The self-repairing properties of mycelium (Elsacker, Zhang, and Dade-Robertson 2023) have the potential to resemble the way termites maintain their nests by blocking off entrances (Penton et al. 2020), repairing external layers that function as sealants, and rebuilding nests after damage (Lubin, Montgomery, and Young 1977; Facchini et al. 2020).

6) ***De-commissioning and re-commissioning***. As mycelium-based composites are biodegradable (Van Wylick et al. 2022), hollows made of this material are compostable and can reintegrate into the soil. Land-managers can remove or replace hollows once they stop being useful as nests for vertebrates. Black woodpecker hollows can have an average lifespan of 18 years (Wesołowski 2011). In spruce trees, which are predominant in the study area, woodpecker hollows can have an average lifespan of just 4 years (*ibid*.). Similar to how these woodpecker hollows fall to the ground after tree breakage, placing the mycelium hollow on the ground could prolong its usefulness as habitat structure by offering opportunities to other organisms, such as invertebrates and plants.

Figure 2. An artificial hollow design that implements a lifecycle approach, proposing to reinstate nesting opportunities on dead trees that had hollows before breaking in a large storm. Image by the authors.

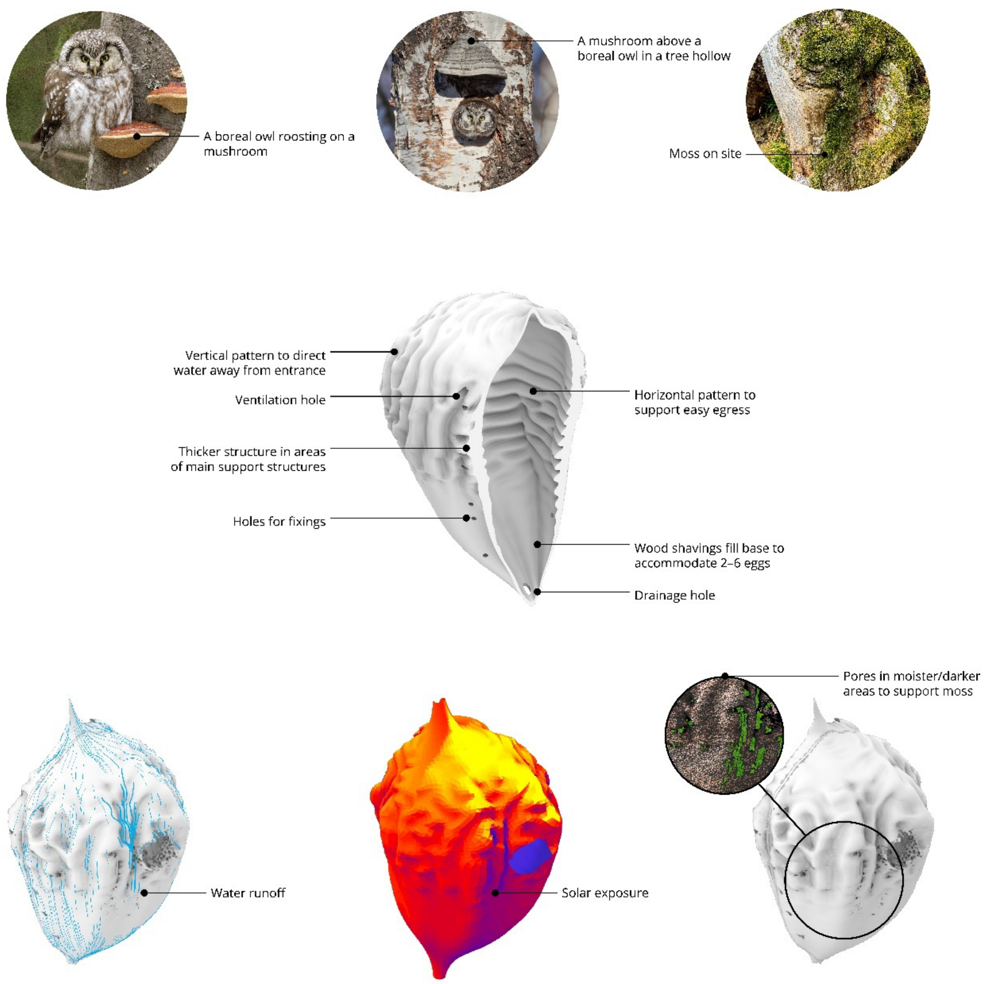

Figure 3. A design for an artificial design based on target species behaviour, site analysis, and simulations of environmental conditions. Image by the authors. Photo of a boreal owl roosting on a mushroom by Tobias Svensson. Photo of a mushroom above a boreal owl by Gary Schultz.

2.3 Making of prototypes

To find suitable ways to make the complex shapes of the proposed artificial hollows, we explored a combination of materials and manufacturing approaches. We produced three prototypes to ensure feasibility and gather information for lifecycle analysis, including weights, volumes, materials, costs, and logistics.

We selected plywood, plastic, and mycelium to compare common and novel materials (Figure 4). Plywood consists of thin wooden layers glued together (Müller, Szemkus, and Hiete 2023). The plastic prototype used polylactide (often referred to as PLA), a material made from plants such as sugarcane or cassava (Morão and de Bie 2019). The mycelium prototype used commercially available reishi/lingzhi (*Ganoderma lucidum*), a native mushroom species that grows in northern Italy (Cartabia et al. 2022; Centre for Agriculture and Bioscience International (CABI) 2021).

We employed a different manufacturing technique for each material, extending our prior applications of computer-aided manufacturing (Parker et al. 2022). We laser-cut plywood sheets, 3D-printed plastic components, and used augmented-reality on smartphones to assemble mycelium blocks. The external dimensions of the prototypes were 700 x 400 x 300 mm and had an entrance diameter of 100 mm, based on dimensions of black woodpecker hollows.

To date, we have installed one prototype made with mycelium as a proof-of-concept and to promote learning (Figure 2). In 2023, a passerine species used the hollow but future field tests will be necessary to understand wildlife responses.

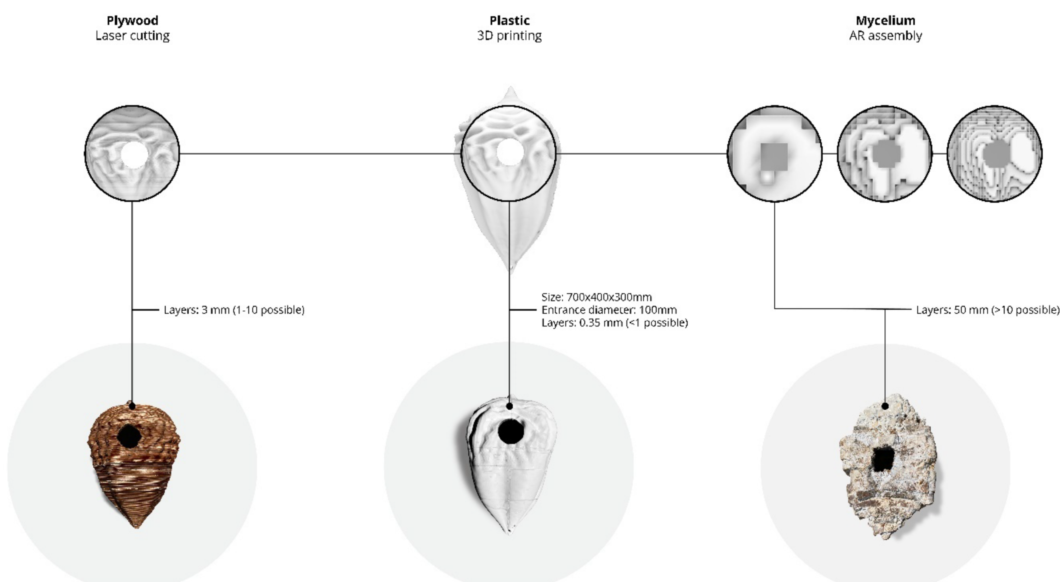

Figure 4. Prototypes, manufacturing approaches, and dimensions of the three prototypes: plywood made from laser cut sheets, plastic made from 3D-printed components, and mycelium assembled using augmented reality. The computer models (top row) indicate the ranges in precision that each manufacturing approach offers. The connecting lines show the level of precision the prototypes used (bottom row). Image by the authors.

2.4 Assessment of prototypes over time

To assess the lifecycles of the three prototypes, we estimated upfront and long-term carbon emissions, embodied energy, monetary costs, and waste production from persistent supply. We calculated cumulative costs of each prototype over 50 years, approximating the amount of time required for faster-growing trees such as aspen to become suitable for woodpecker hollows (Trzcinski et al. 2021; Zawadzki 2024; Rolstad, Rolstad, and Sæteren 2000). Our analysis incorporated the typical lifespans of artificial hollows to estimate the number of replacements needed to maintain continual supply. For example, it takes ten hollows with 5-year lifespans to cover 50 years, but only two hollows with 25-year lifespans. We call these replacements 'cycles', following the terminology in Lindenmayer et al. (2018). We based the analysis on the data provided by cradle-to-gate (CTG), cradle-to-cradle (CTC), and gate-to-grave (GTG) studies (Table 1). These terms are boundary conditions for lifecycle studies, where: 'cradle' involves material extraction, processing, and manufacturing; 'gate' refers to the point at which processed materials are distributed for use as products, or leave the 'factory gate'; and 'grave' describes the end of a product's useful life when it is disposed. We drew from a range of sources to select the most likely input values for our analysis based on the properties of the prototypes we made, then included confidence ranges of possible values that are higher and lower (Table 1). We then included confidence ranges based on other lifecycle analyses of the same material. Our analysis does not include fixings such as straps around the host tree.

Table 1. Prototype inputs for each hollow prototype with assumed values and possible ranges.

	Plywood: Laser cutting	**Plastic:** 3D printing	**Mycelium:** Augmented reality	**Notes and assumptions**
Lifespan	10 years installed (Lindenmayer, Tanton, and Cunningham 1991; Lindenmayer et al. 2009). For reference, some range from 3 years (Lindenmayer et al. 2017) to 20+ years (Korpimäki and Hakkarainen 2012; Goldingay, Thomas, and Shanty 2018; Quin et al. 2020)	25 years installed. For reference, some range from 20+ years (Groom 2010) to 30+ years (estimated) with maintenance (Saunders, Dawson, and Mawson 2023)	5 years installed. For reference, some range from less than a year when composted in soil (Zimele et al. 2020) to several years when coated (Gan et al. 2022)	Actual lifespans of artificial hollows vary widely depending on factors such as weather, maintenance, and build quality
Installations	5 times over 50 years	2 times over 50 years	10 times over 50 years	Uses only one input because including lower and upper values would make resulting ranges too large and trends difficult to interpret
Volume	0.029 m^3 for 18 sheets of 3*600*900mm plywood, with a lower range of 0.024 m^3 for 15 sheets of 3*600*900mm plywood	0.012m^3, ranging from 0.011 m^3 to 0.013 m^3	0.0368 m^3, with a lower range of 0.014 m^3 (using thinner walls)	Volumes can be reduced by using thinner walls, lessening material density, or orienting objects for fabrication more efficiently
Weight	6 kg, ranging from 5 kg to 7 kg	5 kg, ranging from 4 kg to 6 kg	6 kg, with a lower range of 3 kg (assuming reduced wall thickness)	Based on weights of built prototypes and possible reductions in material use
Carbon	1,777 kg CO2-eq/m^3 (R. Crawford, Stephan, and Prideaux 2019) (CTG), ranging from 239 kg CO2-eq/m^3 to 1831kg CO2-eq/m^3 (Müller, Szemkus, and Hiete 2023)	3.3 kg CO2-eq/kg (Benavides, Lee, and Zarè-Mehrjerdi 2020) (CTC), ranging from 0.27 kg CO2-eq/kg (Vink et al. 2007) (CTG) to 4.5 kg CO2-eq/kg (Benavides, Lee, and Zarè-Mehrjerdi 2020) (CTC)	252.09 kg CO2-eq/m^3 (Stelzer et al. 2021) (CTG), ranging from −39.5 kg CO2-eq/m^3 (Livne et al. 2022) (CTG) to 1.72 kg CO2-eq/kg (Früchtl et al. 2023) (CTG)	CO2-eq = carbon dioxide equivalent, a unit to measure greenhouse gas emissions For other ranges and methods to improve performance, see (Carcassi et al. 2022; Alaux et al. 2024)

Energy	26790 MJ/m³ for plywood (R. Crawford, Stephan, and Prideaux 2019) (CTG) Assuming 55.22 kWh, ranging from 31.42 to 74.89 kWh (Kellens et al. 2014) for 2 hours cutting	46 MJ/kg (Benavides, Lee, and Zarè-Mehrjerdi 2020) (CTC) for material, ranging from 27.2 MJ/kg (Vink et al. 2007) (CTG) to 66.66 MJ/kg (Vink and Davies 2015) (CTG) 31.8 MJ/kg (Song and Telenko 2017) for printing, with a lower range of 1 kWh/kg (Cerdas et al. 2017)	860 MJ/m³ (Livne et al. 2022) (CTG), ranging from 652 MJ/m³ (de Bruin, n.d.) to 6 MJ/kg (Enarevba and Haapala 2023) (GTG) 0.02 kWh for 1 full charge of phone/tablet (see energy providers such as Engie)	MJ = megajoules. Includes the energy required to produce the material as well as the energy required to operate machinery (e.g., laser cutters)
Cost	AUD650, ranging from AUD550 to AUD700	AUD1550, ranging from AUD1250 to AUD1900	AUD450, ranging from AUD350 to AUD500	Uses Australian dollars Includes costs of materials, assembly, and installation. Assumes installation costs of AUD50 (ladder) to AUD100 (arborist)
Waste	18.07 kg for offcuts + hollow weight, ranging from 9.16 kg for offcuts only to 19.07 kg, assuming 600 kg/m3 weight of plywood (Parthiban et al. 2019)	6.53 kg (9% of hollow weight during manufacture + hollow weight), ranging from 0.36 kg (30.6% of hollow weight) to 8.08 kg (34.6% of hollow weight during manufacture + hollow weight) (Song and Telenko 2017)	7.97 kg for substrate bags and foil (Stelzer et al. 2021)	Includes manufacturing waste and disposal of hollows Considers only waste to landfill. Lower limits assume recycling or repurposing at end of life Assumes recycling of cardboard packaging

2.5 Comparison of prototypes at scale

We extrapolated the values obtained through the lifecycle analysis of prototypes over time to estimate environmental and economic implications of reinstating the hollows lost in the Paneveggio Natural Park. Here, Storm Vaia damaged approximately 650 hectares of forest (Ente Parco Paneveggio Pale di San Martino 2021). To estimate the number of hollows lost during the storm, we assumed that there were 3 woodpecker-made hollows per hectare (with a confidence range of 1 to 10 (Marchesi et al. 2020)). However, the number of hollows used by secondary nesters can be significantly lower than the number of available hollows (Trzcinski et al. 2021). Therefore, our analysis considered reinstating only the hollows that could be suitable for secondary nesters, or 38% (Ouellet-Lapointe et al. 2012) of the total (with a confidence range of 19% (Cockle, Martin, and Drever 2010) to 43% (Gibbons et al. 2002)). The analysis included costs of recommended annual inspections (Korpimäki and Hakkarainen 2012) and three yearly servicing (Griffiths et al. 2022; Saunders, Dawson, and Mawson 2023). Based on standard commercial fees, we input AUD30 per hollow for inspections and AUD50 per hollow for maintenance and servicing.

3 Results

3.1 Implications of prototypes over time

Our lifecycle analysis revealed variations in the environmental and economic implications upfront and over 50 years (Figure 5). The mycelium prototype was the most sustainable option in both short and long terms. The plywood prototype was projected to emit more carbon dioxide, require more energy, and produce more waste than the plastic and mycelium options. Although the plastic prototype had the highest initial cost, we projected it to become the cheapest option over time due to its longer lifespan. Our analysis also found several factors that would alter the performance of prototypes over time. For instance, the plywood prototype could use lignin-based resins and renewable electricity, organise components to be cut more efficiently, and recycle or repurpose the materials after decommissioning. With these improvements, we projected the plywood prototype to emit comparable amounts of carbon to the plastic and mycelium prototypes. However, the projections for plywood showed that energy use and waste production would remain high, due to the relatively high input values per unit in combination with inevitable offcuts and waste from using lasers to cut irregular shapes. Our projections showed that mycelium prototypes developed through larger-scale production and without high-emission coatings could eventually sequester almost as much carbon as they emit.

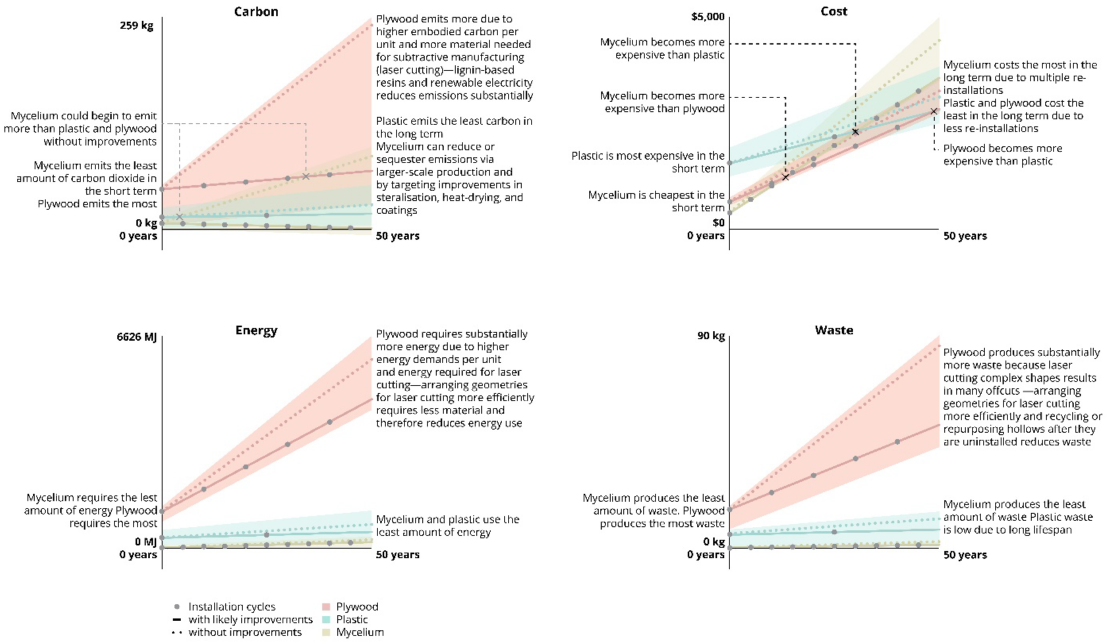

Figure 5. Estimates of carbon emissions, energy use, monetary costs, and waste production upfront and over 50 years for 5 installation cycles of the plywood prototype, 2 installation cycles of the plastic prototype, and 10 installation cycle of the mycelium prototype. The grey dots show the moments of installation when the hollows are replaced. The dashed lines indicate projections based on the initial prototypes without making any improvements. Solid lines indicate projections that incorporate immediately attainable and likely improvements. Coloured areas indicate confidence ranges.

3.2 Implications of prototypes at scale

Our analysis demonstrated notable environmental and economic implications of reinstating hollows, providing important considerations for design choices. We estimated that 741 hollows (confidence range of 123 to 2795) suitable for secondary nesters were lost in Paneveggio Natural Park during Storm Vaia. Given the need to replace artificial hollows at the end of their useful life, maintaining the supply of these lost hollows over the 50-year period would require a total of 3,705 (615–13,975) plywood, 1,482 (246–5,590) plastic, or 7,410 (1,230–27,950) mycelium hollows. At this scale, carbon emissions, energy use, monetary costs, and wastage of laser cutting plywood rendered plastic or mycelium better options according to these criteria (Table 2). Our analysis projected that selecting the most sustainable design option (mycelium) over the cheapest (plastic) would cost an additional AUD592,800 but reduce carbon emissions by 9822 kg, energy use by 295,287 MJ, and waste by 4149 kg over 50 years (Figure 6). Substantial variation in values between design alternatives confirms the importance of assessing the sustainability and feasibility of artificial hollows throughout their entire lifecycles.

Table 2: A comparison estimating total carbon emissions, energy use, monetary costs, and waste production from supplying, maintaining, monitoring, and replacing artificial hollows at 741 sites over 50 years (with lower and upper limits of 123 to 2,795 hollows, respectively).

	Number of hollows	Carbon (kg CO2-eq)	Energy (MJ)	Cost (AUD)	Waste (kg)
Timber: Laser cutting	3,705 (615–13,975)	55,611 (9,268–209,759)	3,474,686 (579,114–13,106,270)	3,840,850 (640,142–14,487,417)	40,531 (6,755–152,877)
Plastic: 3D printing	1,482 (246–5,590)	13,027 (2,171–49,136)	379,540 (63,257–1,431,599)	3,803,800 (633,967–14,347,667)	5,105 (851–19,258)
Mycelium: Augmented reality	7,410 (1,230–27,950)	3,204 (534–12,087)	84,253 (14,042–317,796)	4,396,600 (732,767–16,583,667)	956 (159–3,606)

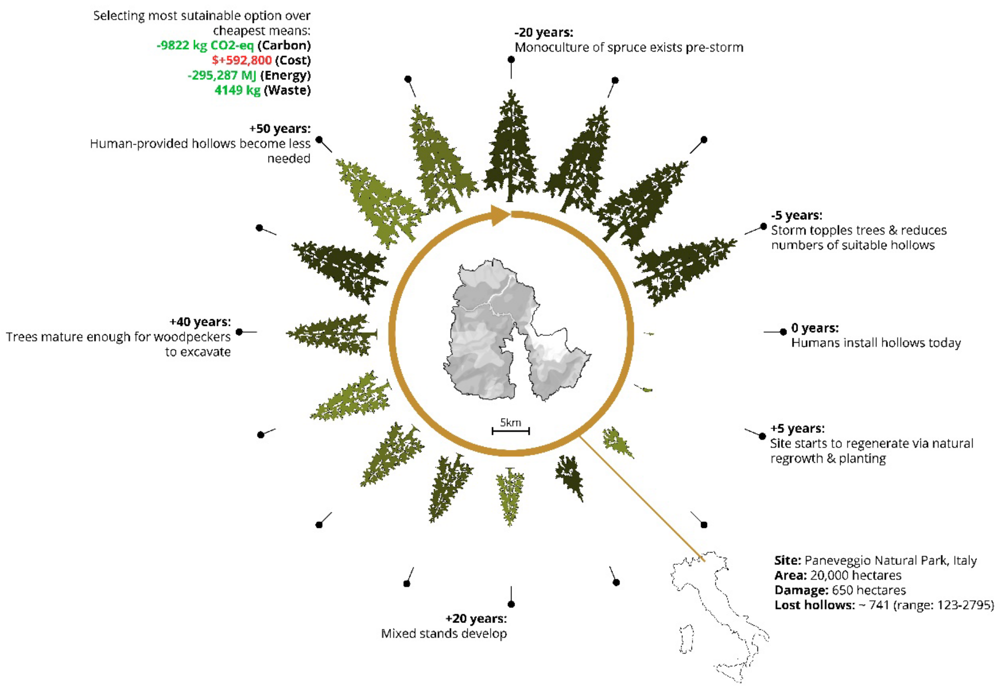

Figure 6. Implications of selecting the most sustainable design option (mycelium) over the cheapest (plastic) to maintain the supply and servicing of 741 hollows over 50 years at Paneveggio Natural Park, Italy.

4 *Discussion*

Our design experiment showed that a lifecycle approach has benefits in all key phases of hollow production, supply, and replacement (Figure 1).

4.1 Designing biologically informed production

Our design experiment highlights the potential of a lifecycle approach to produce artificial hollows that match beneficial properties of natural hollows. In particular, the design of the mycelium hollow presents a new way of thinking about the production of artificial hollows that uses local, renewable, and low-waste materials. The production of this design does not cut trees, rely on plastic or metal that can produce persistent waste, require large land areas for material extraction, or depend on global supply chains. We project the mycelium prototype to use 22% of the energy, emit 25% of the carbon dioxide, and produce 19% of the waste created by the plastic prototypes over 50 years. These findings demonstrate that a lifecycle approach can guide the development of novel designs and materials through a holistic assessment of the potential impacts.

Further, our approach is beneficial to explore more ambitious conservation goals, such as the development of designs that are closer to the properties and processes of natural hollows (Carlsson et al. 2016; Callan, Johnson, and Watson 2023; Jansson et al. 2009). One such goal is to encourage nutrient cycling (Lindenmayer et al. 2018), where excrement, animal remains, and woody debris break down into materials suitable for egg incubation and raising young. These conditions can support beneficial bacteria that indicate nest quality, influence uptake, and support the health of inhabitants (Díaz-Lora et al. 2019). Future sampling is needed to confirm the suitability of mycelial substrates for vertebrate nesters as well as diverse communities of invertebrates, fungi, and bacteria found in hollows (Wetherbee et al. 2022). Considering lifecycles opens possibilities beyond plywood boxes, providing direction to future research and innovation.

4.2 Modelling sustainable supply systems

By making environmental consequences of design options explicit, lifecycle assessments can provide more open ways to assess proposed artificial-hollow programs and support conservation managers to advocate for more sustainable and effective solutions. Sometimes, practitioners with limited budgets may try to maximise impact by installing greater numbers of less expensive hollows. However, our analysis shows the value of assessing the environmental consequences of supplying multiple cycles of hollows, not only the initial costs. For example, at our study site, selecting the most sustainable option (mycelium) over the cheapest (plastic) could reduce carbon emissions by 9,822 kg, energy use by 295,287 MJ, and wastage by 4,149 kg. Such savings will be much higher in other ecosystems where longer timeframes and more hollows are necessary. For example, our scenario specifies 1.14 artificial hollows per hectare over 50 years, whereas other cases require 5 to 10 artificial hollows over 140 to 200 years (Lindenmayer, Tanton, and Cunningham 1991; McKenney and Lindenmayer 1994). The quantification of environmental benefits using our approach could motivate investment in more sustainable options and demand more from developers who use artificial hollows to offset environmental damage caused by construction. For example, studies that demonstrate substantial environmental costs, in addition to already documented inadequacies of some offset programs (Lindenmayer et al. 2017), may reinforce the need to recruit and preserve trees (e.g., Lindenmayer 2016; Gibbons, McElhinny, and Lindenmayer 2010; Kozák et al. 2023).

Improvements to our lifecycle analyses will further assist in the sustainable supply of hollows. For instance, the accuracy of analysis can improve from integration of further information on manufacturers, energy providers, equipment, fixing types, and other factors. A practical expansion could combine the supply and demand of natural and artificial hollows into one integrated system, extending models that simulate staggered recruitment of natural hollows (e.g., Gibbons, McElhinny, and Lindenmayer 2010). Such unified models would assist in the identification of optimal designs, sizes, materials, lifespans, locations, and numbers of artificial hollows in reference to the needs of hollow-dependent fauna in different ecosystems.

4.3 Planning for decommissioning and replacement

A lifecycle approach can help conservation managers decide on the best strategies for sustaining and replacing artificial hollows. Existing approaches rarely consider decommissioning and replacement of artificial hollows. However, we found that assessing artificial hollows over multiple installation cycles can have important implications for design decisions. For example, our results challenge the intuitive assumption that long-lasting hollows are always better and demonstrate that planned decomposition of artificial hollows is possible without prohibitive expense, resource use, waste, and pollution. Even with shorter lifespans, the deployment of mycelium instead of plastic prototypes at our study site could save the amount of carbon sequestered by 162 tree seedlings grown for 10 years and the energy use of a typical family home for 7 years (refer to the Greenhouse Gas Equivalencies Calculator, United States Environmental Protection Agency 2023). Our study estimated that these benefits would come at a cost of almost AUD12,000 per year, but this sum will likely decrease as production improves with experience and scale. Additionally, well-designed procedures for the replacement of biodegradable hollows should not add considerable effort to existing management practices that already require maintenance every three years (Griffiths et al. 2022; Saunders, Dawson, and Mawson 2023), annual checks, or relocation every five years (Korpimäki and Hakkarainen 2012). These examples indicate that lifecycle considerations can help managers plan for the replacement of artificial hollows in ways that balance sustainability with constraints of funding and resource management.

We recommend that managers employ forms of lifecycle assessment to consider a variety of designs with shorter and longer lifespans depending on the target species and site characteristics. In most cases, there will be a significant delay before natural hollows can become available to support wildlife populations (Vesk et al. 2008). In many ecosystems, this time is substantially longer than the lifespan of a typical artificial hollow. Materials with longer lifespans might be appropriate for species that prefer older, non-excavated hollows (Ibarra, Novoa, et al. 2020) or in areas that will not develop hollows in the foreseeable future or at all, such as on buildings. In contrast, regular replacement of short-lived hollows may be advantageous to wildlife. For example, some species show higher survival rates in newly formed hollows (e.g. boreal owls, (Korpimäki and Hakkarainen 2012)), and regular hollow switching can prevent the build-up of parasites or reduce the likelihood of predation (Sonerud 2021). In other cases, there are practical benefits to using short-lived hollows, for example, where severe events such as wildfires and storms have the potential to irreparably damage hollows, producing persistent waste. These strategies exist in application to other habitat structures. One such example are artificial reefs with changeable modules and configurations that can improve over time (Suzdaleva and Beznosov 2021). Another example is the use of temporary habitat-structures made of cardboard that can provide shelter for animals after bushfires without damaging sensitive regeneration areas with heavy objects and the ensuing waste (Hegarty 2022). In many cases, hollows with different lifespans may be most suitable for preserving forest biodiversity (Di Sallo and Cockle 2022; Cockle et al. 2019; Wesołowski 2012) because variety can ensure that there are no shortages in the future (Cockle et al. 2011), and accommodate species with different preferences (Wiebe et al. 2020).

5 Conclusion

This study demonstrates the value of a lifecycle approach in designing and assessing artificial tree-hollows, providing a significant advancement in the field of conservation and habitat restoration. By integrating concepts from biological and technological lifecycles, this approach aids planning and development of sustainable habitat-creation strategies that consider long-term environmental and economic impacts. Numerically modelling the supply of habitat-structures over 50 years at a site of more than 650 hectares, our research demonstrated that lifecycle assessments can usefully inform the design, selection, management, and replacement of artificial hollows as a continuing service. Such analysis is crucial in optimizing the ecological benefits of these structures while minimizing their environmental footprint.

Our findings offer practical insights for a range of stakeholders involved in wildlife conservation, including managers who work to support hollow-dwelling fauna, funders of initiatives that install artificial hollows, developers that deploy nest boxes in offset programs, and makers of artificial habitat-structures. By detailing the implications of different materials and designs, the lifecycle approach introduced in this article can aid decision-makers in choosing more sustainable options that align with local conservation needs and regulatory frameworks.

Looking forward, it is possible and important to expand our lifecycle assessments to include other ways of providing tree hollows by adding carved logs (Central Coast Council 2016), drilling holes (Griffiths et al. 2022), inoculating with fungi (Wainhouse and Boddy 2022), and amending existing cavities (Ellis, Taylor, and Rhind 2022; Valera et al. 2019). A lifecycle approach can broaden the understanding of environmental impacts associated with such interventions and foster the development of more effective conservation strategies.

The lifecycle-informed designing advocated in this article can have applications in many cases. For example, it is important to assess large-scale deployments of perching sites for birds (Holland et al. 2023), artificial habitat-structures in aquatic ecosystems (Cooke et al. 2023; Lemasson et al. 2024), and bricks for birds and insects (Brighton & Hove City Council 2020). By facilitating better-informed decisions, this approach contributes to more effective biodiversity conservation, addressing the urgent need for resilience and long-term sustainability of mitigation measures.

6 Author contributions

Dan Parker: writing – original draft preparation (lead) and review & editing (equal); visualization – images and data presentation (lead); software – computer modelling (lead); methodology – development of methods and creation of models (lead); investigation – performing experiments and collecting data (lead); formal analysis – synthesis of study data (lead); conceptualization – formulation of overarching research goals (supporting). **Stanislav Roudavski**: writing – original draft preparation (supporting), review & editing (equal), and abstract translation to Russian (lead); visualization – images and data presentation (supporting); methodology – development of methods and creation of models (supporting); conceptualization – formulation of overarching research goals (lead). **Chiara Bettega**: writing – review & editing (supporting) and abstract translation to Italian (lead); project administration – coordination of the research planning and execution in Italy (lead). **Luigi Marchesi**: writing – review & editing (supporting); project administration – coordination of the research planning and execution in Italy (supporting). **Paolo Pedrini**: writing – review & editing (supporting); project administration – coordination of the research planning and execution in Italy (supporting). **Mattia Brambilla**: writing – review & editing (supporting) and abstract translation to Italian (supporting); project administration – coordination of the research planning and execution in Italy (supporting). **Kylie Soanes**: writing – original draft preparation (supporting) and review & editing (equal); methodology – development of methods and creation of models (supporting); conceptualization – formulation of overarching research goals (supporting).

7 Acknowledgements

We acknowledge the traditional custodians of the lands on which we work in Italia, Aotearoa/New Zealand, and Naarm/Melbourne, Australia.

We would like to thank Chiara Fedrigotti, Emilio Coser, Helen Wiesinger, and all the staff at MUSE – Science Museum of Trento for their assistance with this project. We also extend our gratitude to Piergiovanni Partel at the Paneveggio-Pale San Martino Natural Park for his support.

We also appreciate the support from all at Deep Design Lab.

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Chapter 6. Better Together: Tools for Participatory Design and Democratic Making of Innovative Habitat-Structures

Dan Parker, Kylie Soanes, and Stanislav Roudavski

Abstract

This article introduces tools to facilitate the co-creation of artificial habitat-structures with communities that include humans, other mammals, and birds. Our work extends interdisciplinary efforts aiming to support urban biodiversity by incorporating both human and nonhuman stakeholders into design processes. The involvement of nonhuman participants in design, referred to here as more-than-human-design, is a significant challenge that requires the development of new methods. Connecting innovative work in design and ecology, we explore how inclusive, community-led, and 'open' approaches can enhance more-than-human design. We propose that open-design tools can (1) incorporate nonhuman expertise, (2) facilitate design in diverse communities, and (3) and promote the sharing and reuse of beneficial practices. To test these hypotheses, we developed and tested an online customisation tool for co-creating habitat structures with animals that do not construct their own nests. Through a community workshop in Melbourne, Australia, we revealed several benefits, constraints, and future possibilities. We demonstrate the potential for open design tools to incorporate distinct cultural practices of human and nonhuman stakeholders, extend existing conservation initiatives, and enhance the implementation of artificial habitat-structures. By reimagining design as an extension of citizen science, this article offers tangible ways for nonhuman stakeholders to influence actions that affect communities of multiple species. Our work contributes to the ongoing development of design for multispecies cohabitation, putting forward pathways to further test and refine novel approaches.

1 Introduction

This article introduces open and inclusive strategies for the design, implementation, and enhancement of artificial habitat-structures for urban wildlife. Combining expertise in design and ecology, we present an online tool that facilitates the co-creation of nesting sites with communities that include humans, other mammals, birds, and other organisms. This initiative supports interdisciplinary efforts to forge more equitable urban environments by incorporating both human and nonhuman stakeholders into the design process (Labaeye 2019; Apfelbeck et al. 2020; Hernandez-Santin et al. 2023). The concept of more-than-human (also called interspecies and ecocentric) design prioritises the needs of nonhuman stakeholders and goes beyond the notion of nature-based solutions that primarily benefit human interests (Herrmann-Pillath, Hiedanpää, and Soini 2022; Roudavski 2022; 2021). More-than-human approaches are vital as nonhuman entities often lack representation in decision-making processes, leading to individual suffering, species extinctions, and broader ecological crises (White 2013; Wienhues 2018; Baxter 2005). Our work advances research on the development of open, inclusive methods to envision futures that are respectful of all stakeholders and provide nonhuman beings with opportunities to shape decisions (Herrmann-Pillath et al. 2023; Fazey et al. 2020). We propose that technology-supported methods that encourage wide participation and share effective practices can enhance equity in design, make design outcomes more acceptable to key stakeholders, promote innovation, and amplify the impact of designs on large scales.

We recognise the potential of more-than-human design to fulfill these needs by leveraging principles from participatory design and related approaches such as co-design, crowdsourcing, citizen science, and citizen design (Mueller et al. 2018). Participatory practices focus on the creation, testing, and refinement of designs through collaboration with human stakeholders. These practices acknowledge humans as experts in their own experiences and aim to incorporate their perspectives and knowledge (Simonsen and Robertson 2013). Further benefits can follow from the integration of experiences, expertise, and contributions of nonhuman stakeholders such as birds, insects, and plants (Choi, Braybrooke, and Forlano 2023; Rice 2018; Maller 2018; Bastian et al. 2017; Veselova and Gaziulusoy 2021; 2022; Foth 2017). To illustrate, designers can provide structures that integrate birds' ability to recognise suitable tree branches (Roudavski and Holland 2023) or insects' expertise in excavating nests that suit their needs (Parker et al. 2023). These examples show how nonhuman participation offers a means to overcome anthropocentric biases that can make design ineffective, harmful, and unfair (Roudavski 2022; 2020).

Designers face a significant challenge in involving nonhuman participants, who differ from humans in body structure, behaviour, and information-processing capabilities. Researchers are exploring the potential for more-than-human participation across various fields, including smart cities (Clarke et al. 2019; Heitlinger et al. 2018; Tomitsch et al. 2021), forest monitoring and management (Westerlaken et al. 2022), animal-computer interaction design (Westerlaken and Gualeni 2016), human-computer interaction design for ecosystems (Tomlinson et al. 2022), speculative design (Romani, Casnati, and Ianniello 2022), urban planning (Olsen 2022), and the design of urban landscapes (Haldrup, Samson, and Laurien 2022). The development of concrete methods for more-than-human design can gain from sharing knowledge, expertise, workflows, and demonstrators to encourage innovation and adoption (Roudavski 2018). To date, design for biodiversity lacks a continuous transfer of expertise from nonhuman beings to human experts skilled in technology, and further to local multispecies communities that can implement and sustain this knowledge in practice.

In this article, we explore the potential to apply 'open source' and 'open design' principles to more-than-human design, as these approaches facilitate reuse and ensure wide reach. Current efforts in open design aim to democratise innovation and production, granting access to design knowledge, processes, and outputs to a broader range of human stakeholders (Bakırlıoğlu and Kohtala 2019). This accessibility allows anyone to study, create, reuse, modify, or distribute designs (Mies, Bonvoisin, and Jochem 2019). Open design reshapes the relationship between designers and users, enabling the customisation of toolkits for personal or communal needs (Bakırlıoğlu and Kohtala 2019; Boisseau, Omhover, and Bouchard 2018). This approach blurs the line between professionals and amateurs, boosts knowledge sharing, speeds up innovation, and promotes a do-it-yourself (DIY) maker culture by reducing or eliminating the need for trained professionals (Dai et al. 2020). Digital design and manufacturing facilities, including maker spaces and fabrication laboratories (FabLabs), support this democratisation (Boisseau, Omhover, and Bouchard 2018). DIY approaches to building or modifying objects can appealing for reasons of affordability, control, enjoyment, and accomplishment (Wolf and McQuitty 2011). The 'do-it-together' (DIT) concept enhances DIY practices by focusing on collective action and mutual support (Singer et al. 2021; Jarvis 2018). Such collaborative, open-source infrastructures encourage positive interactions, dialogue, and collective creativity that leads to innovative solutions (Thackara 2005). Opportunities to extend 'open' approaches to enhance more-than-human design are visible in existing open-access environments such as games, online platforms, and mobile applications. These tools help humans care for plants and animals (Bier et al. 2023), create customisable hydroponic gardens (Takeuchi 2019), 3D print habitat structures for bees (Ilgün and Schmickl 2024), and envision greener, eco-friendly urban environments that support multiple species (Davidová et al. 2022; Roudavski, Holland, and Rutten 2018; Istrate and Hamel 2023; Sanchez 2019).

To explore this topic, we ask: How can open-design tools enhance more-than-human design? We hypothesise that open systems can (1) incorporate nonhuman expertise through numerical modelling, (2) facilitate design in diverse communities via online customisation interfaces, and (3) promote the sharing, reuse, and enhancement of practices with openly available data protocols, standards, evidence, recipes, and demonstrators. We explore how online configurators can achieve these capabilities. Online configurators are websites that enable non-designers to adapt computer models for their needs. Typically, these configurators focus on human requirements, such as selling houses or furniture (Sandrin et al. 2017; Jimenez-Moreno 2021). However, they can also facilitate customised production of habitat structures intended for nonhuman users such as bees (Space 10 2020). In this study, we developed and tested an online configurator for co-creating habitat structures with birds and mammals that do not construct their own nests.

2 Methods

To test our hypotheses, we explored how open-design tools can aid collaboration among human and nonhuman stakeholders in three steps. First, we focused on tree hollows because they provide a characteristic case that poses challenges to more-than-human design. Second, we developed an online configurator for tree hollows as a proof-of-concept to devise and implement techniques for more-than-human design. Third, we tested the configurator in a community workshop to understand its feasibility, benefits, constraints, and future possibilities.

2.1 Tree hollows as a characteristic challenge for design

The supply of tree hollows is a complex yet exemplary subject for testing our hypotheses on the integration of nonhuman expertise, democratisation of design, and enhancement of knowledge sharing. Hollows are vital but increasingly threatened habitat structures globally, formed through complex interactions within ecosystems (Remm and Lõhmus 2011; Lindenmayer et al. 2013). Conservationists install human-made or 'artificial' tree hollows in urban areas to mitigate the shortage caused by the scarcity of large, old trees, which significantly impacts many species (Reynolds et al. 2019). While existing designs of artificial hollows support some species and are valuable in community-led projects—as shown by DIY nest-box guides and ongoing monitoring by volunteers—they often require improvements (Lawton et al. 2022; Beck 2011; Macak 2020). Challenges include difficulty in installation (Lindenmayer, Tanton, and Cunningham 1991; Central Coast Council 2016), failure to attract target species (Gautschi et al. 2022), susceptibility to overheating (Griffiths 2022; Flaquer et al. 2014), and structural breakdown soon after installation (Lindenmayer et al. 2009; Le Roux et al. 2015; Saunders, Dawson, and Mawson 2023). Industrially manufactured nest boxes are affordable and easy to produce without specialised skills (Briskie, Shorey, and Massaro 2014; Barker and Wolfson 2013). However, they differ significantly from natural habitats (Griffiths et al. 2018).

The reliance on human expertise can be insufficient to produce designs that reflect the complex ecological interactions and usage patterns associated with tree hollows. In this context, interspecies collaboration holds promise to develop effective innovations for habitat improvement. There is a need for designs that better reflect the characteristics of sites, behaviours of target species, local climates, geometric attributes, and material properties of natural hollows. Such flexibility is important because many animals exhibit complex behaviours, have regional variations, and are developing new traditions in human-altered environments (Keith and Bull 2017). Computer-aided design and manufacturing can create customised designs that address these needs but often require specialised equipment and expertise not typically available in community-led projects (Parker et al. 2022). Our case study investigates how open-design tools can enhance the creation of artificial tree hollows by combining the benefits of advanced technologies with the advantages of broad participation.

2.2 An online configurator as an example of open-design tools

To examine the benefits of open-design tools, we developed an online configurator that aids the design and creation of artificial hollows. This platform enables a wide range of human stakeholders to customise and construct hollows that meet local requirements while incorporating nonhuman expertise (Figure 1). Our goals for the configurator included:

- **Integrating diverse forms of knowledge:**
    - Utilising current scientific understanding to set design constraints.
    - Enabling computational simulations to evaluate performance.
    - Facilitating the testing of prototypes by nonhuman users.
- **Maximising accessibility and supporting distributed innovation:**
    - Tailoring difficulty levels to match human capabilities and resource constraints.
    - Providing quick, gratifying results to enhance user experience.
    - Enabling customisation through investigative exploration.
    - Aiming for high precision.
    - Setting ambitious development goals.
    - Supporting easy comparisons of design and production options.
    - Fostering positive interactions within the community.
    - Facilitating educational opportunities for all stakeholders.
- **Enabling broad generalisation and reuse of knowledge:**
    - Supporting the testing and comparison of all design strategies.
    - Ensuring the persistence and sharing of knowledge.
    - Encouraging the reuse of design insights and methodologies.

Aiming to meet these goals, the configurator enables human users to choose options that best suit their circumstances and local ecosystems. The interface provides options to select target species, tailor the design for locally specific behaviours, and shape the design to conform to the trees or human-made objects on which they will be installed (Figure 2). Users can also select different materials to suit their context, choose the most appropriate manufacturing methods that leverage local capabilities, and decide who will assemble the hollows based on time or budget constraints. The configurator also provides options for monitoring, offers guidance on suitable installation locations for the hollows, and supports the collection and sharing of performance data, which helps refine ongoing and future designs. To achieve these ongoing improvements, the configurator supports the translation of nonhuman needs into designs by allowing knowledge to flow between stakeholders, services, and outputs (Figure 1).

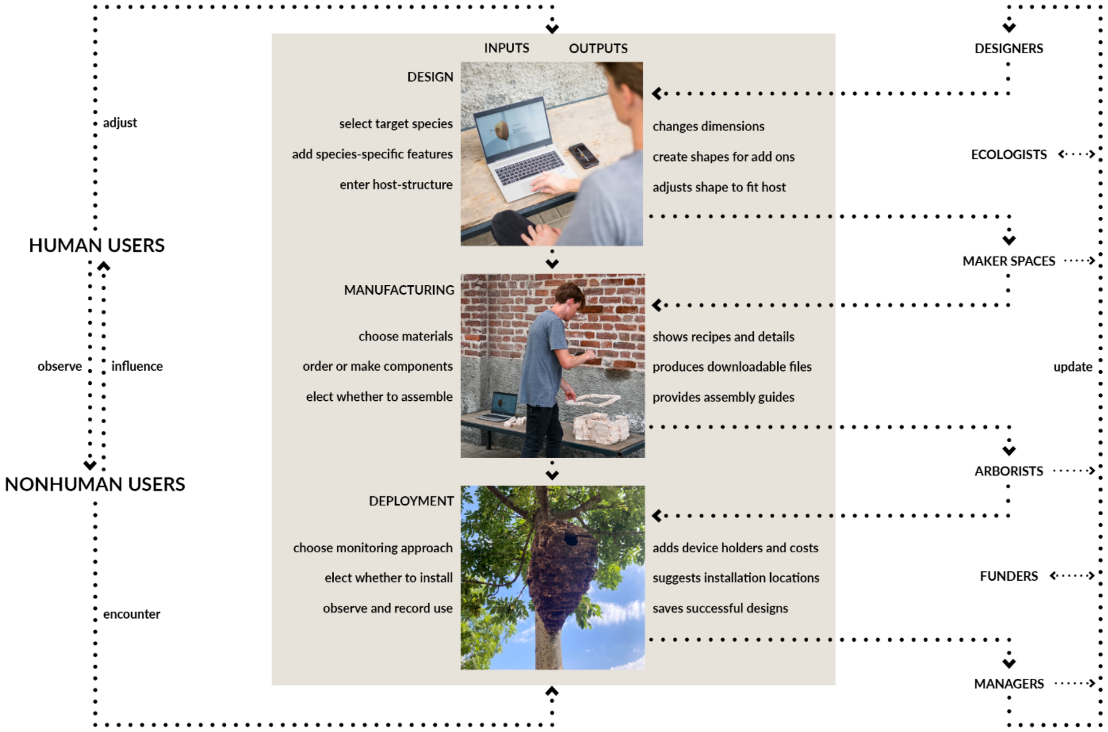

Figure 1. The online configurator for artificial hollows in use. Middle: The stages of design, manufacturing, and deployment as guided by the online configurator on laptops and/or smartphones. Left: Human users can adjust multiple inputs to the configurator based on their circumstances as well as nonhuman needs. Right: Human stakeholders and facilitators can influence the outputs of each stage, integrating diverse knowledges into the continual development of the configurator.

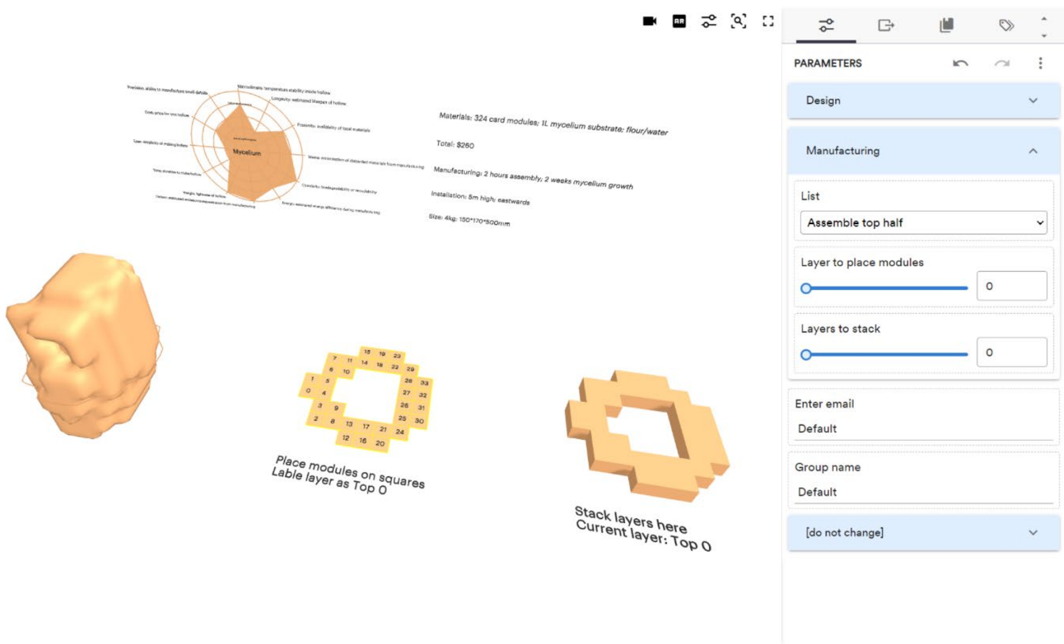

Figure 2. The interface of the configurator. Left: a model of the artificial hollow. Top: details on the hollow's performance including cost and required materials. Bottom: guides for do-it-yourself assembly. Right: parameters to adjust designs and order artificial-hollow materials.

2.3 A community workshop to test the configurator

The final step aimed to evaluate whether the configurator could meet the expectations set by our hypothesis through a trial run involving human participants. For this purpose, we hosted a public hollow-building workshop to explore the configurator's advantages and limitations. Workshops are an effective way to test open-source tools, as they promote the exchange of knowledge and the generation of new ideas (Dai et al. 2020). The workshop took place in Melbourne, Australia, and lasted three hours. Its 25 attendees included high-school pupils, university students, Indigenous land managers, volunteers involved in environmental initiatives, council workers, and local residents (Figure 3).

During the workshops, participants utilised the configurator to choose target species from a list of locally significant species and to tailor the design accordingly. The list included the laughing kookaburra (*Dacelo novaeguineae*), spotted pardalote (*Pardalotus punctatus*), red-rumped parrot (*Psephotus haematonotus*), eastern rosella (*Platycercus eximius*), musk lorikeet (*Glossopsitta concinna*), and ringtail possum (*Pseudocheirus peregrinus*). The configurator constrained the sizes of the hollows and entrances in line with local guidelines (Birdlife Australia 2016). It automatically configured each hollow to have a slight forward lean and a textured interior to facilitate easier egress for the inhabitants.

The configurator's customisation features allowed participants to modify three-dimensional models based on their research or prior experiences with the species. Adjustable options included: additional entrances to provide lookout and feeding points for less dominant chicks

(Kouba, Bartoš, and Zárybnická 2014); entrance types tailored to whether the species typically uses hollows in branches or trunks; entrance orientations to shield against prevailing weather conditions or to guide fledglings to lower branches; perches at the entrances for easier access or to guard the entrance (Wildlife Kate 2023); and predator guards to deter nest usurpation by common, non-native species (Bailey and Bonter 2017; Bailey et al. 2020).

Participants used the configurator's assembly guides to create prototypes of the hollows from laser-cut cardboard modules infused with mycelium. To test an innovative assembly approach, some attendees used augmented reality goggles to follow the guides quickly and without the need for training (Figure 3). To evaluate the configurator's effectiveness in facilitating innovative design in practice, we incorporated Australian Reishi (*Ganoderma steyaertanum*), a fungus indigenous to Australia (Queensland Government 2022). We chose this material for its cost-effectiveness, lightweight, low waste, non-toxicity, and biodegradability.

Subsequent prototypes experimented with alternative designs and installation of hollows at several locations. After initial collaborative prototyping, we showcased the configurator's ability to handle multiple design iterations and advanced manufacturing processes. To do this, we used a test process that utilised stackable layers of 3D printed wood (Figure 4) to minimise contamination from manual handling, which can introduce mould and inhibit mycelial growth. In defining such designs, the configurator automatically distributes interlocking elements that simplify and accelerate assembly, eliminating the need for toxic adhesives or nails. The lightweight, layered design not only conserves materials and reduces printing time but also accommodates various fill materials, such as soil and hempcrete. To aid decisions on the selection of materials, the configurator provides real-time feedback on various performance metrics that indicate each hollow's suitability for target ecosystems, environmental sustainability, and feasibility to produce (Figure 4). The performance metrics enable comparisons of the benefits and limitations of each option in order to select context-appropriate hollows. This design process allowed us to achieve enhancements and find ways of integrating human and nonhuman needs.

Figure 3. Scenes from the workshop that trailed techniques for designing and making artificial hollows with the configurator. Left: Using augmented reality to guide the assembly (images by Alex Quan). Top-right: Using the configurator on laptop to guide assembly. Bottom-right: Artificial prototypes made of mycelium.

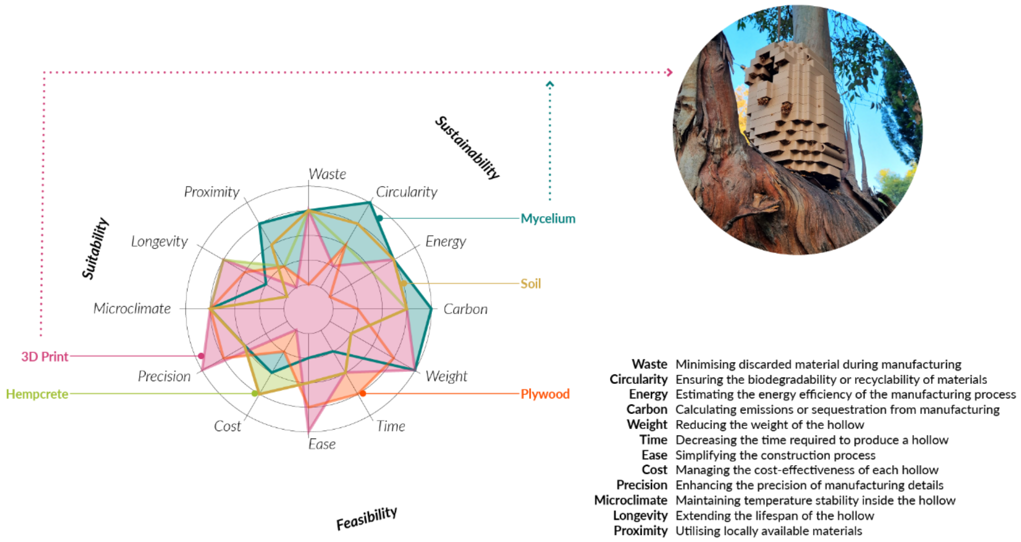

Figure 4. Performance metrics to guide the selection of designs. Left: Assessment of each hollow's suitability for target ecosystems, environmental sustainability, and feasibility to produce, where the outer bands indicate better performance (unpublished data). Right: An artificial hollow prototype combining the options of 3D-printed wood and mycelium.

3 Findings

We found that an online configurator can incorporate nonhuman expertise, facilitate design in diverse communities, and promote the sharing and reuse of beneficial practices.

3.1 Integrating human and nonhuman expertise

The public workshop trialling our online configurator for artificial hollows allowed us to test the ability for open-design tools to integrate interdisciplinary human innovations with nonhuman expertise. Our findings reveal that open-design tools can incorporate local knowledge of both human and nonhuman stakeholders into design outcomes. For instance, the configurator enables users to tailor designs based on their experiences at the site and their observations of the target species. As an example, one design includes a shelf intended to accommodate the observed behaviour of a nearby kookaburra diving to catch a fish and then resting on a ledge outside its natural hollow to eat (Figure 5). Another design incorporates a protruding platform at the entrance, inspired by behaviours of kookaburras peering out from and perching outside their hollows. These adaptations are crucial as animals within the same species often exhibit regionally specific behaviours that vary regionally. Place-specific behaviours can emerge through individuality, available resources, climatic conditions, or socially learned traditions that biologists understand as culture (Keith and Bull 2017). The nesting traditions of birds and bees are an example of such variation (Healy 2022; Di Pietro et al. 2024). As our configurator shows, open-design tools can adapt to and reflect these diverse behaviours.

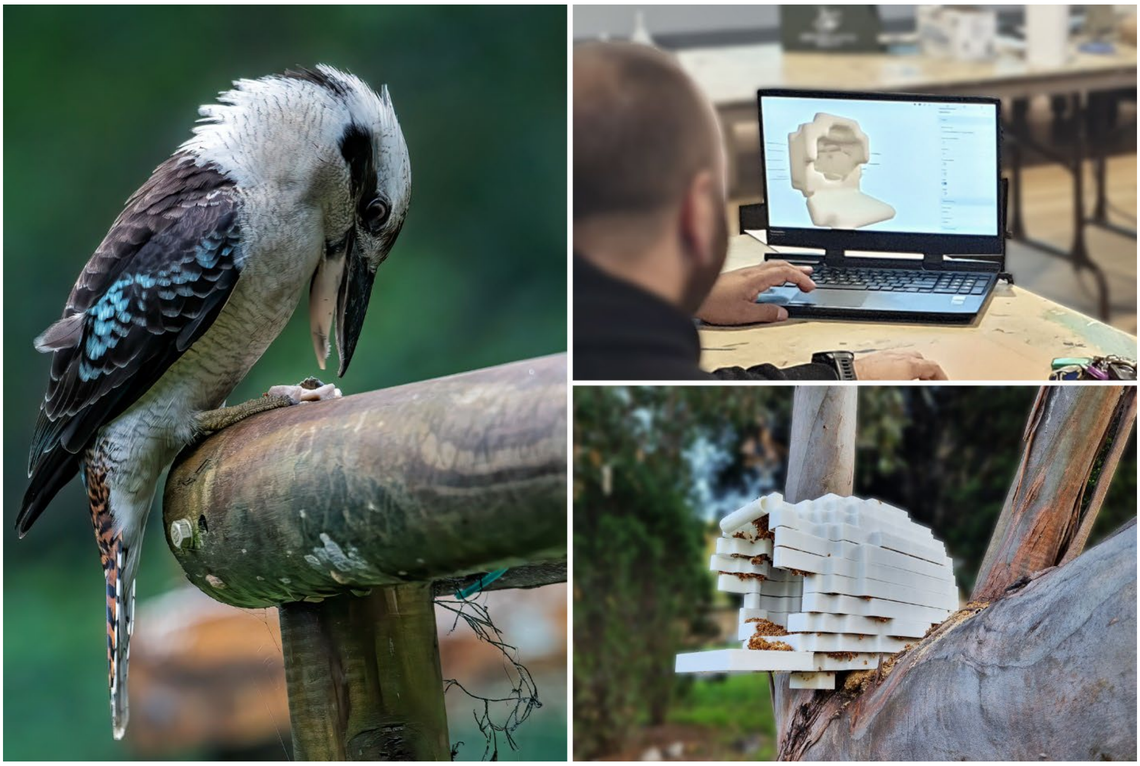

Figure 5. The configurator integrating local knowledge. Left: A kookaburra feeding on a platform (image by Tracie Louis). Top-right: A group at the workshop using the configurator to add a platform to an artificial hollow design, based on their observations of kookaburra feeding practices at natural hollows nearby. Right: A physical prototype of the artificial hollow design for kookaburras produced in the workshop.

3.2 Enhancing collaboration

Our study demonstrates how open-design tools can enable ecologists, designers, management professionals, and local community members including birds and mammals to collaborate effectively on design processes. These tools can serve as repositories for shared knowledge from various fields, facilitating mutual learning and insight sharing among stakeholders. This collaborative environment supports brainstorming, prototyping, feedback, and iterative improvements, fostering more inclusive and democratic design outcomes.

During its development and testing at the public workshop, the configurator provided valuable learning opportunities which can extend the functionality of the configurator. For example, after gaining insights into local ecologies, participants suggested designs for entrance protrusions to protect inhabitants from predators and rough exteriors to assist climbing birds. Such tailored features could help nonhuman inhabitants learn how to use new artificial structures. Importantly, the configurator's inclusive functionality empowers both human and nonhuman users to have a say in design. On one hand, its guides and material recipes encourage humans to engage more confidently in custom design, installation, and monitoring tasks. On the other hand, the responses of wildlife can inform the selection, retention, and ongoing adjustments of design. These outcomes demonstrate how open design tools integrate diverse knowledges to promote the enhancement of artificial habitat-structures.

3.3 Enabling accessibility and generalisation

We found that open-design tools can adapt to the needs of multiple species in different regions. The configurator allows users to tailor designs to sites, species, and constraints. By providing access to numerical data on sustainability, feasibility, and suitability, it enables users to weigh options and choose designs that best fit their contexts. For instance, participants expressed willingness to invest more effort and resources into creating more suitable hollows. Hempcrete, due to its affordability and durability, is ideal for budget-conscious projects or installations requiring low-maintenance solutions. Mycelium, valued for its sustainability, is better for projects with longer timelines, those targeting species with frequent nesting changes, or in areas that require fire-resistant materials. Conversely, 3D-printed plastic can be suitable for locations where natural hollows are scarce and the need is urgent while precision is necessary to meet the requirements. The online configurator enhances accessibility to these technologies and materials by providing easy-to-follow guides and employing distributed manufacturing techniques. These techniques can allow users to customise, download, and locally produce designs using maker spaces or home devices at costs and production times comparable to mass production (Ratto and Megan 2014; Conte et al. 2022). As such, the configurator proves to be useful for both individual and community design efforts by enabling users without professional design training to undertake sophisticated design projects that would be otherwise unfeasible. By simplifying access to design knowledge and techniques, the configurator enables communities everywhere to collaborate on creating tailored solutions for various locations and species. This approach could not only enhance the functionality of designs but also broaden participation in ecological conservation efforts.

4 Implications

Our online configurator for artificial hollows showcases the potential of open tools to enhance more-than-human design. In discussing the implications, we look to citizen science as a model of a democratised approach to tackling large and complex challenges, illustrating the potential for similarly inclusive approaches in design. Citizen science has transformed various fields, including conservation, by involving a broad base of contributors (de Sherbinin et al. 2021; von Gönner et al. 2023). However, citizen science is often challenging, particularly locally, at specific sites (Criscuolo et al. 2023). It can also be difficult to translate participatory findings into effective and innovative conservation actions (Taylor et al. 2021; Brooks, Waylen, and Mulder 2013).

By reimagining design as an extension of citizen science, we align with the goal to create large platforms that function as commons of collective intelligence (Gill, Baeck, and Whittington 2022; Urban et al. 2022). This reframing allows open-design tools to leverage distributed intelligence and more-than-human perspectives to influence practical actions for future cohabitation. The following sections discuss the implications of our findings, focusing on incorporating distinct cultural practices, enhancing integration with existing initiatives, and building toward large-scale solutions.

4.1 Designing for interspecies cultures

Using the configurator to illustrate the possibility, our study has demonstrated a variety of methods to integrate both human and nonhuman knowledge into the design process. We have employed computer modelling to incorporate current scientific data as constraints on designs and enable adjustments based on observations of wildlife. In our test, open-design tools have proven effective in fostering interspecies understanding, resulting in designs that meet the needs of nonhuman stakeholders more accurately. For instance, our configurator has provided practical tools that enable nonhuman stakeholders to influence design decisions, enhancing the ability of the designs to respond to the nuances of ecological relationships. Lab experiments, field observations, traditional ecological knowledge, and established patterns of long-term collaborative cohabitation can provide further sources of nonhuman expertise in support of deign.

We encourage further research into the design of artificial habitats that integrate the cultural preferences of both human and nonhuman stakeholders. For example, artificial hollows can incorporate human cultural expressions through decorations showcasing the work of local and Indigenous artists (Houtz, Mady, and Uehling 2021; Brunswick Valley Landcare 2021). Artificial hollow designs can also recognise nonhuman aesthetic preferences, for example, by mimicking the structures of natural nests (Roudavski and Parker 2020). However, balancing these preferences can be challenging. Projects like insect hotels or designer birdhouses often prioritise human aesthetics over the practical needs of nonhuman users, compromising the structures' suitability for the intended species (Ljokkoi 2023; Laubach and Laubach 1999).

In contrast, there is potential for co-creating environments that enable animals to physically alter their habitat structures (Thoren 2018; Ljokkoi 2023). For instance, could materials like mycelium allow birds such as kookaburras and pardalotes shape their own nesting spaces, mirroring the way they excavate soft substrates in soil or termite nests? This approach emphasises the need for a more balanced relationship in design practices, where human experts recognise and incorporate contributions provided by nonhuman beings. By doing so, we acknowledge these stakeholders as experts in their own ecological niches, capable of influencing and enhancing the design of their habitats. This integration of human and nonhuman expertise can rebalance the power dynamics often present in design and decision-making processes, ensuring that designs address needs in an equitable manner. This integrated approach to design not only promotes biodiversity but can also enhance the usability and acceptance of artificial habitats for both human and nonhuman stakeholders.

4.2 Designing for collective improvement

Our research underscores the point that optimal design is impossible and highlights the necessity for design systems that are capable of improvement, adaptation, and flexibility in response to new circumstances and knowledge. Current approaches to design often fall short in supporting these dynamic needs, but open-design tools are well positioned to fill this gap. These tools encapsulate the same principles as citizen science, emphasizing agility, persistence, continuous engagement, and the integration of complex data sets, while fostering innovation, inclusivity, and ambitious visions for better futures.

However, the effectiveness of these technological capabilities depends on their communal adoption, testing, and maintenance. For technologies to be utilised, they must be accessible and appealing. Designers, acting as intermediaries, can play a critical role in fostering a creative and inclusive exchange of knowledge across various disciplines and stakeholders (Frantzeskaki 2019). Open-design tools enhance accessibility to diverse communities of practice and support distributed innovation by aligning design challenges with the available capabilities and resources of users, offering quick and rewarding results, enabling customisation through exploratory investigation, and aiming for high precision and ambitious goals. These tools also facilitate positive community interactions and educational opportunities for stakeholders.

The configurator developed as part of this study exemplifies how habitat solutions can evolve within eco-social systems. It supports continuous learning and improvement, which is crucial for adapting to dynamic urban environments (Landry 2008; Herrmann-Pillath, Hiedanpää, and Soini 2022; Herrmann-Pillath et al. 2023). Installations of designs derived from the configurator facilitate the testing of prototypes by nonhuman users in their habitats and provides means for the incorporation of their feedback into iterative designing.

Furthermore, open-design tools have promising applications in educational settings, enhancing existing curricula that allows direct engagement with conservation efforts through the construction, installation, and monitoring of nest boxes (The Cornell Lab of Ornithology 2023; Victorian Curriculum and Assessment Authority 2019; MacDonald et al. 2020). The use of streaming media to showcase nesting in artificial hollows exemplifies engaging educational content that can inspire proactive environmental stewardship (Zárybnická, Sklenicka, and Tryjanowski 2017).

Looking ahead, linking configurators to data-driven initiatives could significantly enhance their utility. Databases detailing species locations, conservation statuses, and human-cultural relationships with wildlife could inform the selection of target species and refine design objectives (Belbin et al. 2021; Wyndham et al. 2016). Access to extensive, open-access data sets on nesting behaviours (Bailey, Larson, and Bonter 2024) could drive the iterative evolution of design, populating the configurator with successful models for future adaptation and reuse. This integration of open-design tools not only signifies a leap in technical innovation but also promotes a deeper social connection to nature, fostering a broader, more engaged approach to conservation.

4.3 Designing for bespoke precision at scale

Our study demonstrates that it is feasible to scale the production, installation, and impact of artificial habitat-structures without sacrificing the specific needs and inputs of local human and nonhuman stakeholders. This goal requires a balance between bespoke solutions tailored to specific eco-social systems and the capacity to have a broad, scalable impact. This balance necessitates systems that effectively support the propagation and sharing of knowledge.

Through online tools, open design can support the reuse of knowledge by ensuring ease of understanding, utilising common software, adopting innovative tools, and integrating resulting processes into standard educational frameworks. Future work will need to test and compare different approaches, incorporate expertise through standards, preserve knowledge through clear protocols and archiving, encourage knowledge sharing through open access resources, facilitate communal support for ideation and troubleshooting, develop inclusive financial models, and recruit new participants.

Conservation efforts are increasingly driven by community involvement, necessitating tools that allow direct participation. Our configurator enables the production of artificial hollows that are ecologically sustainable and tailored to local ecosystems while remaining accessible to a diverse range of stakeholders. It offers various participation levels, from DIY to professional, thereby enabling individuals and community groups to create habitat structures in their backyards or local parks, as well as developers and councils to integrate these structures into larger habitat-restoration projects. There is a risk that organisations whose activities damage the environment will use artificial habitat-structures as devices for greenwashing (Watchorn, Duncan, and Cowan 2023). For this reason, some makers of artificial habitat-structures turn down some funding propositions. This reality highlights the need for further consideration on the openness, intellectual property, and funding models of the configurator going forward.

The configurator has further possible applications as a toolkit for households, enhancing conservation efforts on private lands where social acceptance and direct participation are crucial (Kamal, Grodzińska-Jurczak, and Brown 2015; Goddard, Dougill, and Benton 2010). Tools and activities that are enjoyable, engaging, and educational can encourage broader citizen involvement in environmental projects (Land-Zandstra, Agnello, and Gültekin 2021; Thackara 2005; Maund et al. 2020). In keeping with this evidence, our approach supports the implementation of community-led ecological restoration projects by accommodating inclusive participation and building relationships based on local knowledge.

In sum, our online configurator for artificial hollows exemplifies an open-design tool that not only addresses the technical needs but also fosters a more collaborative approach to design that does not exclude nonhuman stakeholders. This aligns with our broader objectives of integrating diverse perspectives, challenging traditional design hierarchies, and supporting communal decision-making processes that yield improved habitat structures (Whitelaw, Hwang, and Le Roux 2021). Through this work, we contribute to the ongoing dialogue and development in the fields of biodiversity-inclusive and more-than-human design, paving the way for future initiatives that will further test and refine these innovative approaches.

5 Author contributions

Dan Parker developed the models and tools, led the writing, and produced the visual materials. Kylie Soanes provided ecological guidance and helped with editing. Stanislav Roudavski directed the research and contributed to the writing and editing.

6 Acknowledgments

Moonee Valley City Council funded the hollow-building work. We thank Moonee Valley City Council, Urban Bushland Initiative, and all other organisers and attendees of the workshop. We acknowledge the Wurundjeri people who are the Traditional Custodians of the Land on which this research took place. We appreciate the collaboration with the Narrap Rangers and the Wurundjeri Woi Wurrung Cultural Heritage Aboriginal Corporation.

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Conclusion

This thesis set out to develop design approaches that can support multispecies cohabitation. Designing for multispecies cohabitation is increasingly important as human activities continue to degrade ecosystems and impact the wellbeing of countless organisms. I approached this challenge by conceptualising and testing prosthetic habitat-structures as a means to co-create built environments with and for nonhuman stakeholders. The case studies and design experiments in this thesis demonstrate that prosthetic habitat-structures have the potential to facilitate mutually beneficial coexistence among humans, birds, fungi, plants, and other organisms. The chapters achieved this by producing:

1. **provocations** into the potential to address the challenges of human-wildlife coexistence through design that considers more-than-human cultures;
2. **frameworks** to grapple with the practical and ethical challenges of designing for cohabitation through identification of nonhuman capabilities;
3. **recommendations** for designing cities as places for multispecies cohabitation through ethnographies of communities where humans and other beings cohabit successfully;
4. **workflows** to improve designs of prosthetic habitat-structures through utilisation of computational technologies;
5. **models** to aid the design and assessment of prosthetic habitat-structures through lifecycle analysis of long-term and large-scale regeneration proposals; and
6. **toolkits** that make innovative techniques for nonhuman participation more plausible and accessible through online platforms to co-create prosthetic habitat-structures.

These outcomes confirm my hypotheses and demonstrate the benefits of integrating more-than-human culture, creativity, and collaboration into design. The chapters in this thesis develop new knowledge that:

a. deepens the understanding of how designing for interspecies cultures can help humans and nonhumans live together better;
b. enhances the implementation, evaluation, and adoption of prosthetic habitat-structures by employing computer-assisted techniques; and
c. reveals how collaboration with human and nonhuman stakeholders can make multispecies cohabitation more plausible, feasible, and desirable.

This research benefits a range of multispecies communities and contributes to a growing body of interdisciplinary work seeking to cultivate places where these communities are abundant, diverse, and flourishing. The novel approaches to designing for cohabitation established in this thesis can assist researchers and practitioners working in biological conservation and the built environment. Practical benefits from this thesis include:

a. goals and evaluative practices for professionals in ecology and the built environment seeking ways to make cities more biodiverse;

b. prototypes that birds and mammals have already used, as well as avenues to develop better prototypes in the future; and
c. tangible, reusable, and extendable techniques for researchers aiming to give nonhuman stakeholders a say in design and decision-making.

The impact and outreach of the projects in this thesis demonstrate further benefits that extend beyond the requirements of the degree. I produced several creative works formally recognised as research, co-authored summary articles, gave public talks, featured in the media, established partnerships with councils and industry, received multiple grants, and won awards (listed below). These outcomes highlight the far-reaching value of the work in this thesis and demonstrate an appetite for further research and innovation in support of multispecies cohabitation.

Creative works

Parker, Dan, and Stanislav Roudavski. 2022. *Bio-Digital Manufacturing of Tree Hollows*. Exhibit. Trentino, Italy: MUSE – Science Museum of Trento.

Parker, Dan, and Stanislav Roudavski. 2022. *Biomaterials for Replacement Habitats*. Installation and online. Newcastle, United Kingdom: OME, Hub for Biotechnology in the Built Environment, Newcastle University.

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Dissemination

Parker, Dan. 2022. "Designing Custom Homes for Hollow-Dwelling Animals." *Architect Victoria*, Design for All Life, 3: 48–51.

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Presentations

Parker, Dan, and Stanislav Roudavski. 2023. "What Is It Like to Be an Owl … in a Human World? Mutual Support, Conflict, and Design Imagination in Interspecies Communities." Online

presentation presented at the Conference of the Australasian Animal Studies Association: Animal Cultures, Sydney, Australia.

Parker, Dan. 2023. “Prosthetic Habitat-Structures.” Presented at the Dialogue on Future Urbanism, Melbourne School of Design, AU.

Parker, Dan. 2022. “Designing for Multispecies Cohabitation.” Invited talk presented at the Anthropology of Sustainability Lectures, University of Bologna.

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Media

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